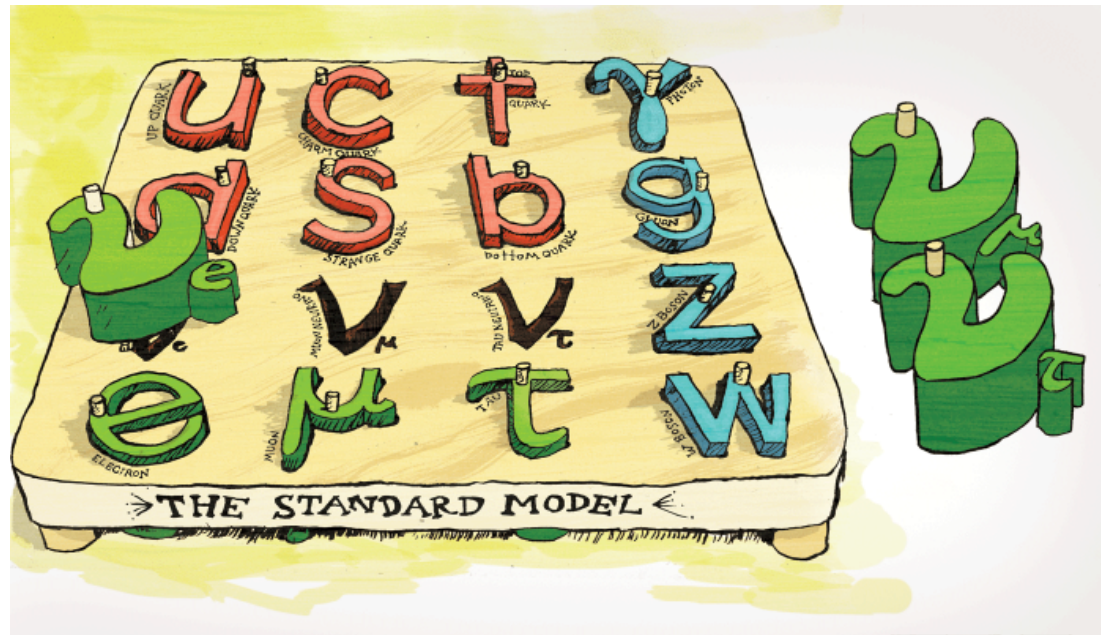


Neutrino Physics Beyond the Standard Model



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July 12, 2017

Very Brief Outline

- New Physics in the Neutrino Sector!
- What is the New Physics in the Neutrino Sector?
 - More New Physics in the Neutrino Sector?

Questions are Most Welcome at Any Time!

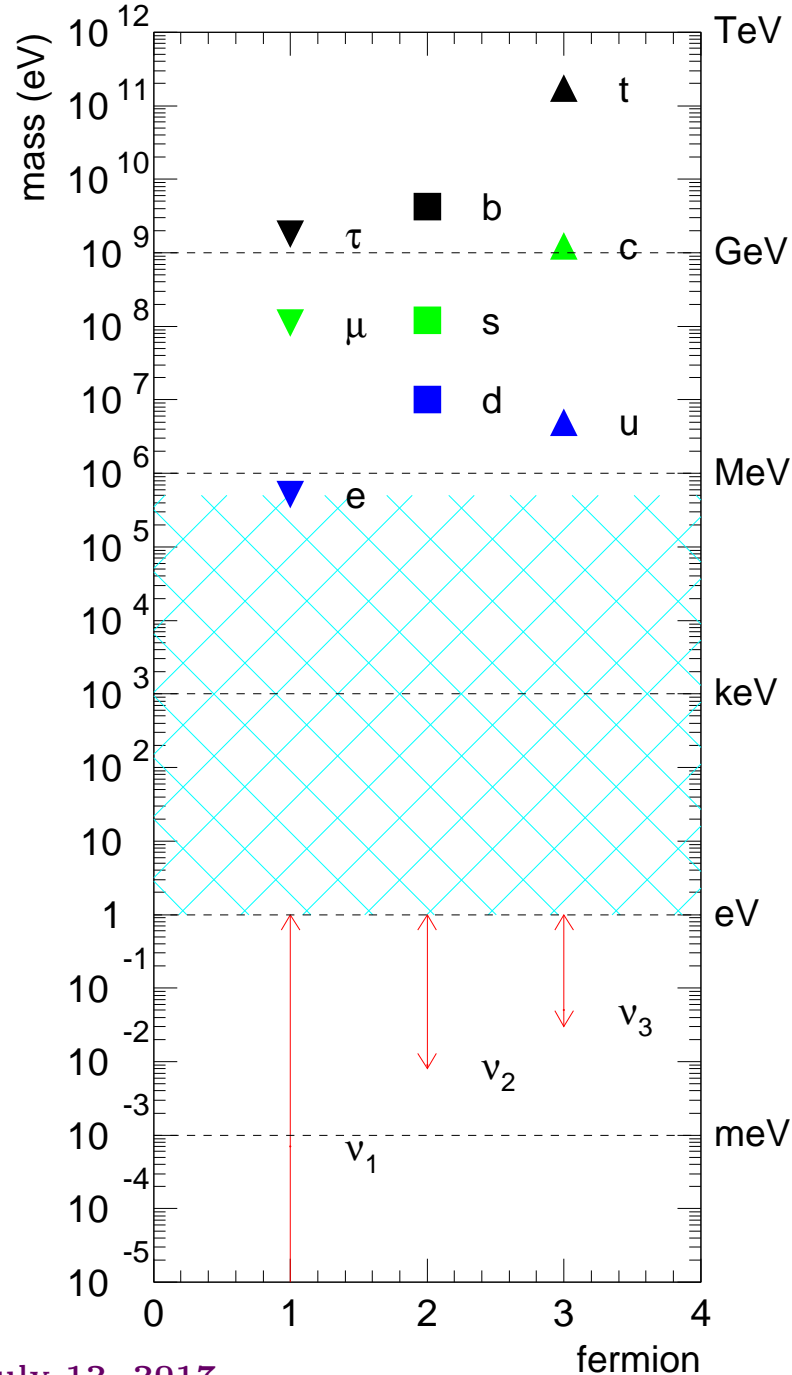
Something Funny Happened on the Way to the 21st Century

ν Flavor Oscillations

Neutrino oscillation experiments have revealed that **neutrinos change flavor** after propagating a finite distance. The rate of change depends on the neutrino energy E_ν and the baseline L . The evidence is overwhelming.

- $\nu_\mu \rightarrow \nu_\tau$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$ — atmospheric and accelerator experiments;
- $\nu_e \rightarrow \nu_{\mu,\tau}$ — solar experiments;
- $\bar{\nu}_e \rightarrow \bar{\nu}_{\text{other}}$ — reactor experiments;
- $\nu_\mu \rightarrow \nu_{\text{other}}$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_{\text{other}}$ — atmospheric and accelerator expts;
- $\nu_\mu \rightarrow \nu_e$ — accelerator experiments.

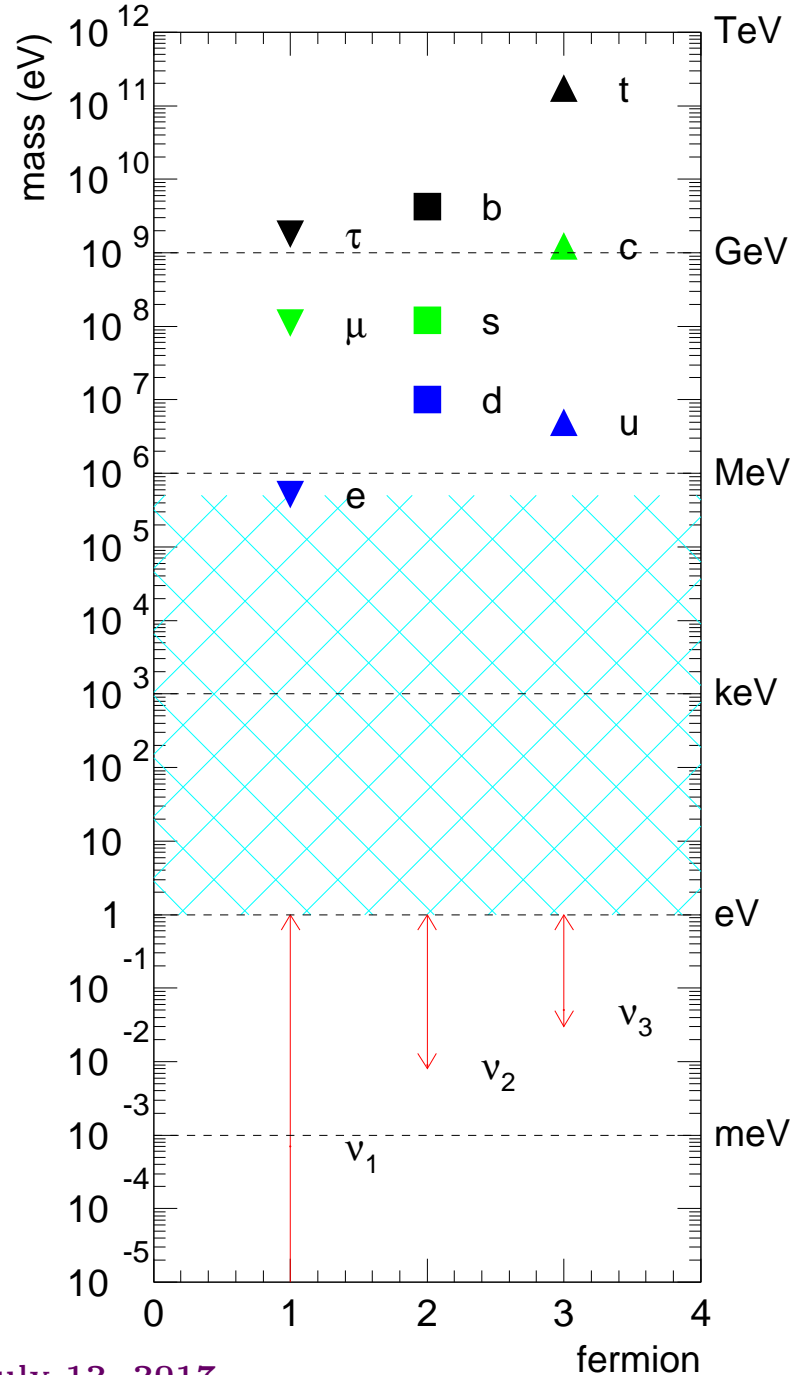
The simplest and **only satisfactory** explanation of **all** this data is that neutrinos have distinct masses, and mix.



NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?



NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?



NEW PHYSICS

Evidence for Physics Beyond the Standard Model

1. The expansion rate of the universe seems to accelerate, both early on (inflation) and right now (dark energy).
2. Dark matter seems to exist.
3. Why is there so much baryonic matter in the universe?
4. Neutrino masses are not zero.

1. and 2. are consequences of astrophysical/cosmological observations. It is fair to ask whether we are sure they have anything to do with particle physics.

3. is also related to our understanding of the early history of the universe and requires some more explaining.

4. is the most palpable evidence for new physics.

What is the New Standard Model? [ν SM]

The short answer is – WE DON'T KNOW. Not enough available info!



Equivalently, there are several completely different ways of addressing neutrino masses. The key issue is to understand what else the ν SM candidates can do. [are they falsifiable?, are they “simple”?, do they address other outstanding problems in physics?, etc]

We need more experimental input.

Neutrino Masses, EWSB, and a New Mass Scale of Nature

The LHC has revealed that the minimum SM prescription for electroweak symmetry breaking — the one Higgs double model — is at least approximately correct. What does that have to do with neutrinos?

The tiny neutrino masses point to three different possibilities.

1. Neutrinos talk to the Higgs boson very, very **weakly** (Dirac neutrinos);
2. Neutrinos talk to a **different Higgs** boson – there is a new source of electroweak symmetry breaking! (Majorana neutrinos);
3. Neutrino masses are small because there is **another source of mass** out there — a new energy scale indirectly responsible for the tiny neutrino masses, a la the seesaw mechanism (Majorana neutrinos).

Searches for $0\nu\beta\beta$ help tell (1) from (2) and (3), the LHC, charged-lepton flavor violation, *et al* may provide more information.

Fork on the Road: Are Neutrinos Majorana or Dirac Fermions?

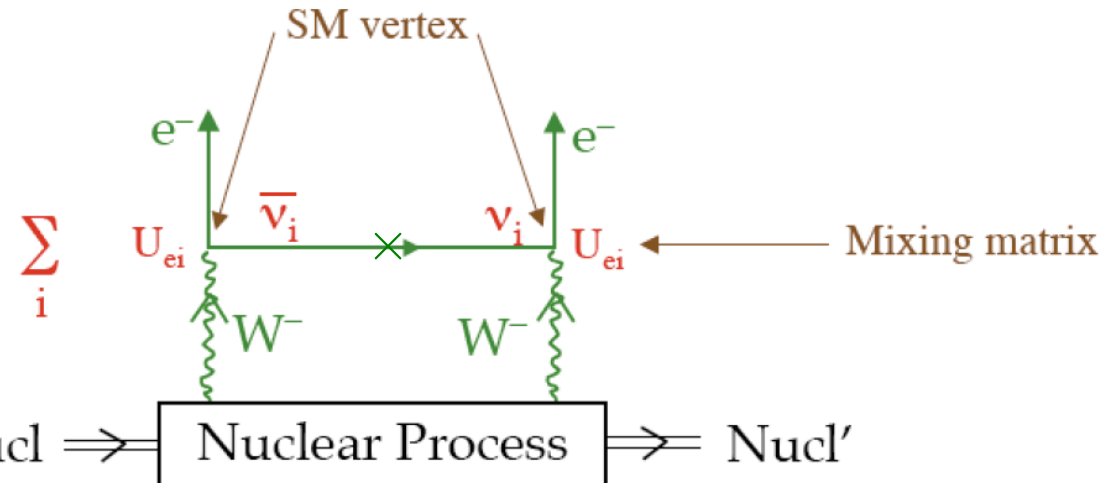
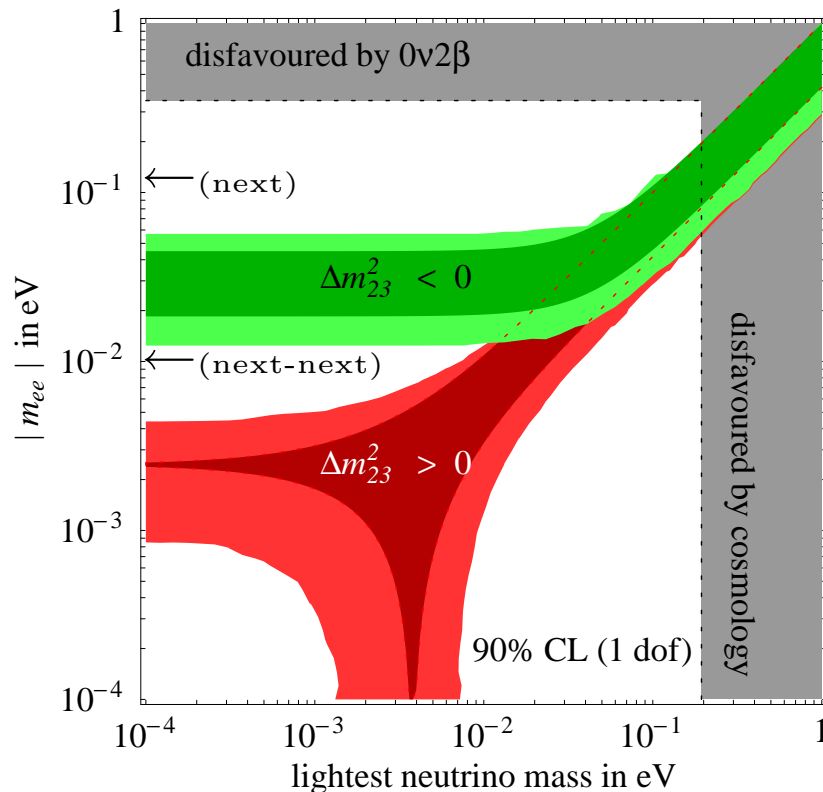


Search for the Violation of Lepton Number (or $B - L$)

Best Bet: search for

Neutrinoless Double-Beta

Decay: $Z \rightarrow (Z + 2)e^- e^-$



Helicity Suppressed Amplitude $\propto \frac{m_{ee}}{E}$

Observable: $m_{ee} \equiv \sum_i U_{ei}^2 m_i$

Plus Help from Oscillations (Mass Hierarchy)

Any other competitive probes? Model Dependent

We Will Still Need More Help ...



Piecing the Neutrino Mass Puzzle

Understanding the origin of neutrino masses and exploring the new physics in the lepton sector will require unique **theoretical** and **experimental** efforts, including ...

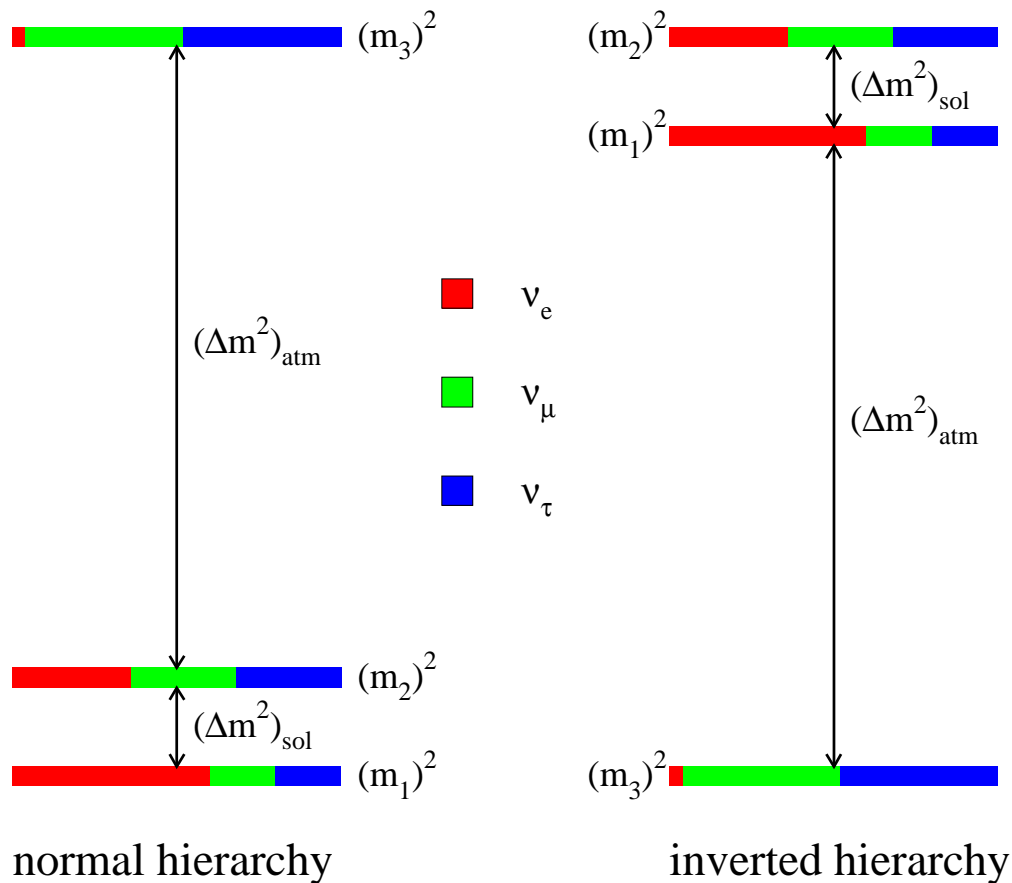
- understanding the fate of lepton-number. Neutrinoless double beta decay!
- a comprehensive long baseline neutrino program, towards precision oscillation physics.
- other probes of neutrino properties, including neutrino scattering.
- precision studies of charged-lepton properties ($g - 2$, edm), and searches for rare processes ($\mu \rightarrow e$ -conversion the best bet at the moment).
- collider experiments. The LHC and beyond may end up revealing the new physics behind small neutrino masses.
- cosmic surveys. Neutrino properties affect, in a significant way, the history of the universe. Will we learn about neutrinos from cosmology, or about cosmology from neutrinos?
- searches for baryon-number violating processes.

HOWEVER...

We have only ever objectively “seen” neutrino masses in long-baseline oscillation experiments. It is the clearest way forward!

Does this mean we will reveal the origin of neutrino masses with oscillation experiments? We don’t know, and we won’t know until we try!

Understanding Neutrino Oscillations: Are We There Yet? [NO!]

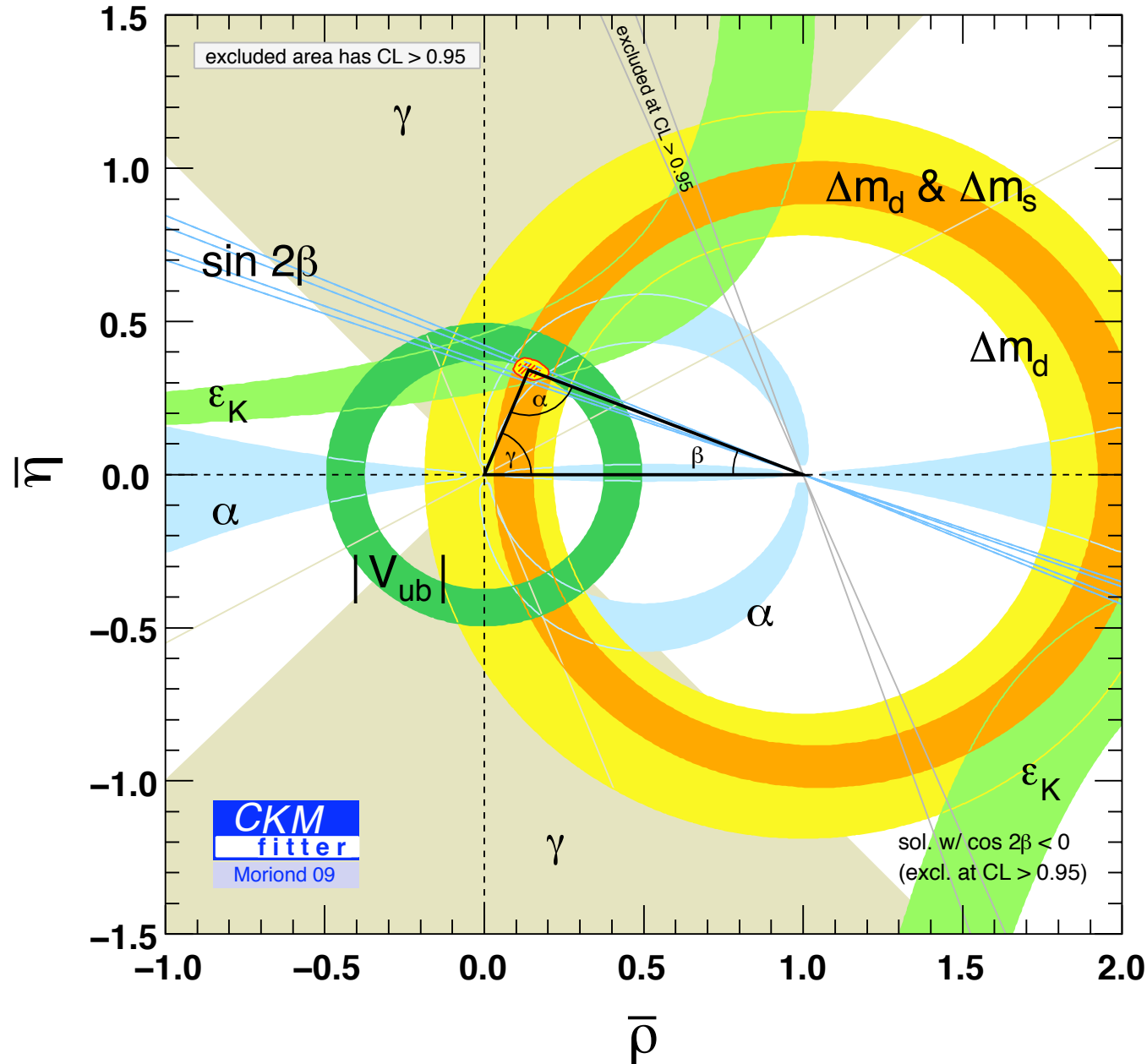


- What is the ν_e component of ν_3 ? ($\theta_{13} \neq 0!$)
- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi?$) ['yes' hint]
- Is ν_3 mostly ν_μ or ν_τ ? [$\theta_{23} \neq \pi/4$ hint]
- What is the neutrino mass hierarchy? ($\Delta m_{13}^2 > 0?$) [NH weak hint]

\Rightarrow All of the above can “only” be addressed with new neutrino oscillation experiments

Ultimate Goal: Not Measure Parameters but Test the Formalism (Over-Constrain Parameter Space)

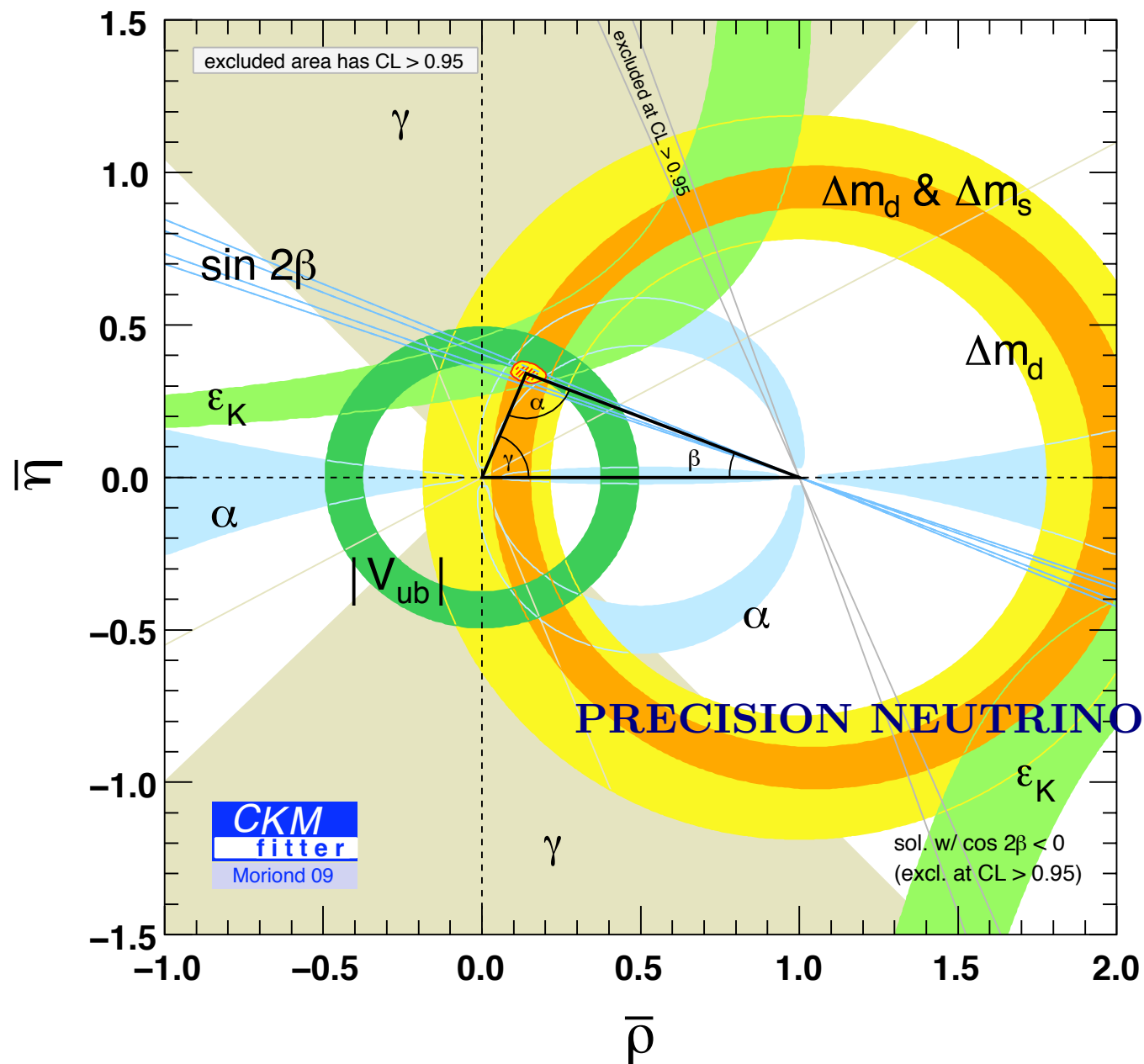
What we ultimately want to achieve:



We need to do this in
the lepton sector!

HOW?

What we ultimately want to achieve:



We need to do this in
the lepton sector!

PRECISION NEUTRINO EXPERIMENTS

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

What we have **really measured** (very roughly):

- Two mass-squared differences, at several percent level – many probes;
- $|U_{e2}|^2$ – solar data;
- $|U_{\mu2}|^2 + |U_{\tau2}|^2$ – solar data;
- $|U_{e2}|^2 |U_{e1}|^2$ – KamLAND;
- $|U_{\mu3}|^2 (1 - |U_{\mu3}|^2)$ – atmospheric data, K2K, MINOS;
- $|U_{e3}|^2 (1 - |U_{e3}|^2)$ – Double Chooz, Daya Bay, RENO;
- $|U_{e3}|^2 |U_{\mu3}|^2$ (upper bound \rightarrow evidence) – MINOS, T2K.

We still have a ways to go!

CP-invariance Violation in Neutrino Oscillations

The most promising approach to studying CP-violation in the leptonic sector seems to be to compare $P(\nu_\mu \rightarrow \nu_e)$ versus $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$.

The amplitude for $\nu_\mu \rightarrow \nu_e$ transitions can be written as

$$A_{\mu e} = U_{e2}^* U_{\mu 2} (e^{i\Delta_{12}} - 1) + U_{e3}^* U_{\mu 3} (e^{i\Delta_{13}} - 1)$$

where $\Delta_{1i} = \frac{\Delta m_{1i}^2 L}{2E}$, $i = 2, 3$.

The amplitude for the CP-conjugate process can be written as

$$\bar{A}_{\mu e} = U_{e2} U_{\mu 2}^* (e^{i\Delta_{12}} - 1) + U_{e3} U_{\mu 3}^* (e^{i\Delta_{13}} - 1).$$

[I assume the unitarity of U , $U_{e1} U_{\mu 1}^* = -U_{e2} U_{\mu 2}^* - U_{e3} U_{\mu 3}^*$]

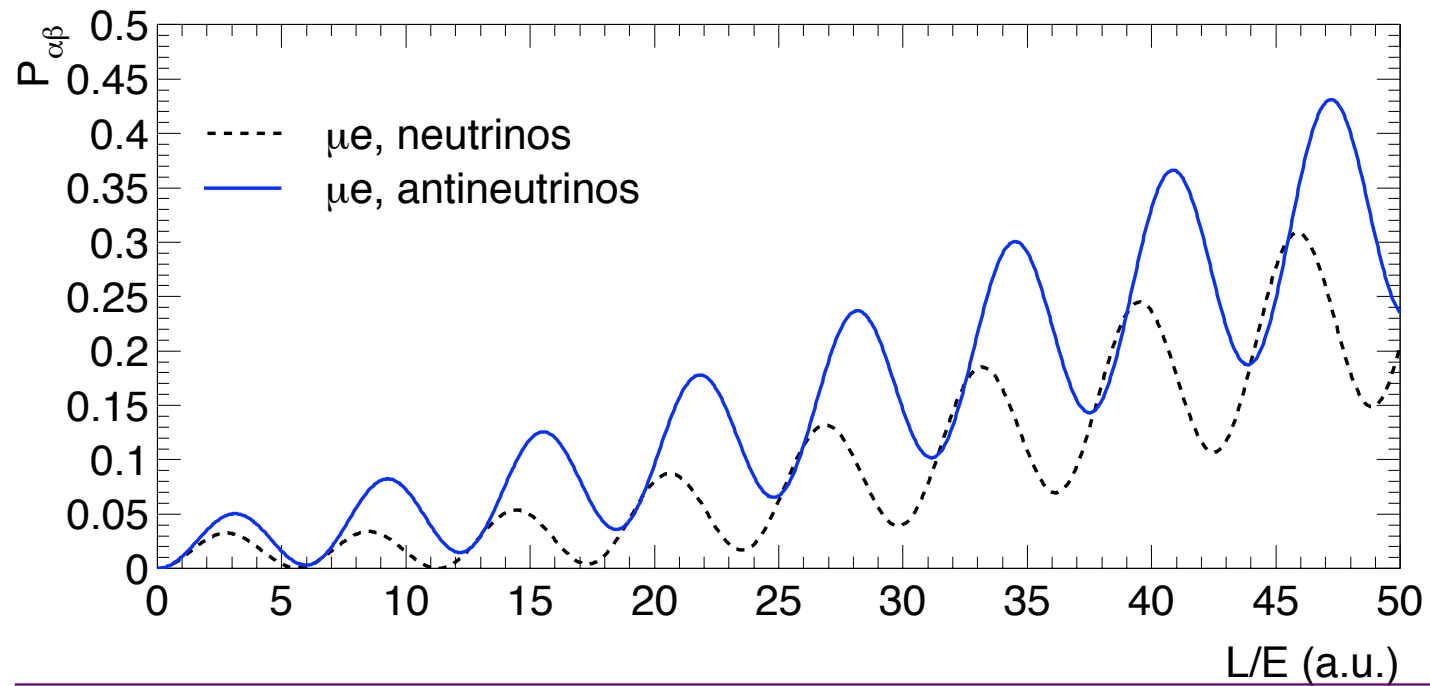
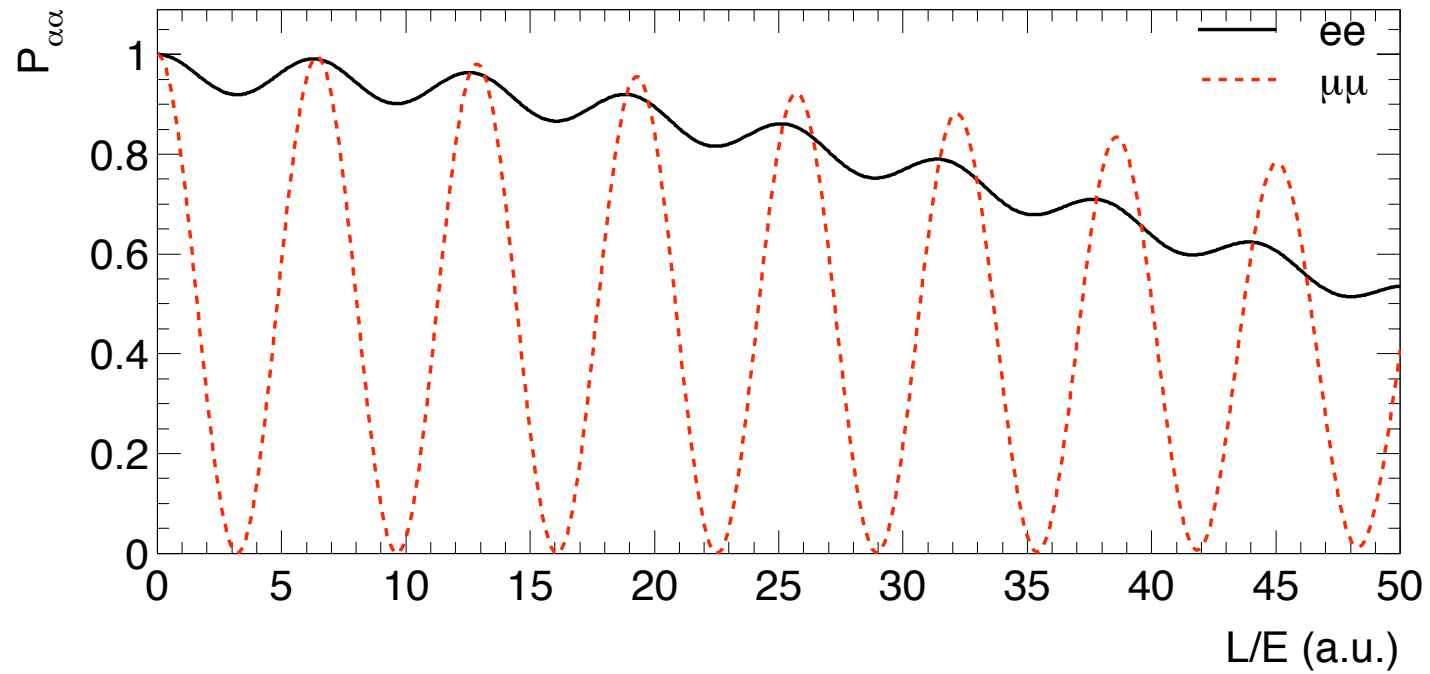
In general, $|A|^2 \neq |\bar{A}|^2$ (CP-invariance violated) as long as:

- Nontrivial “Weak” Phases: $\arg(U_{ei}^* U_{\mu i}) \rightarrow \delta \neq 0, \pi$;
- Nontrivial “Strong” Phases: $\Delta_{12}, \Delta_{13} \rightarrow L \neq 0$;
- Because of Unitarity, we need all $|U_{\alpha i}| \neq 0 \rightarrow$ three generations.

All of these can be satisfied if we pick the right neutrino energy and baseline.

In practice this is quite hard. One amplitude is much larger than the other ($|U_{e3}|$ turned out to be too large)...

Bottom line: we need to measure the oscillation probabilities at the percent level.



Golden Opportunity to Understand Matter versus Antimatter?

The SM with massive Majorana neutrinos accommodates **five** irreducible CP-invariance violating phases.

- One is the phase in the CKM phase. We have measured it, it is large, and we don't understand its value. At all.
- One is θ_{QCD} term ($\theta G\tilde{G}$). We don't know its value but it is only constrained to be very small. We don't know why (there are some good ideas, however).
- Three are in the neutrino sector. One can be measured via neutrino oscillations. 50% increase on the amount of information.

We don't know much about CP-invariance violation. Is it really fair to presume that CP-invariance is generically violated in the neutrino sector solely based on the fact that it is violated in the quark sector? Why?

Cautionary tale: “Mixing angles are small”

What Could We Run Into?

- New neutrino states. In this case, the 3×3 mixing matrix would not be unitary.
- New short-range neutrino interactions. These lead to, for example, new matter effects. If we don't take these into account, there is no reason for the three flavor paradigm to “close.”
- New, unexpected neutrino properties. Do they have nonzero magnetic moments? Do they decay? The answer is ‘yes’ to both, but nature might deviate dramatically from ν SM expectations.
- Weird stuff. CPT-violation. Decoherence effects (aka “violations of Quantum Mechanics.”)
- etc.

[Very Quick Aside...]

The Short Baseline Anomalies

Different data sets, sensitive to L/E values small enough that the known oscillation frequencies do not have “time” to operate, point to unexpected neutrino behavior. These include

- $\nu_\mu \rightarrow \nu_e$ appearance — LSND, MiniBooNE;
- $\nu_e \rightarrow \nu_{\text{other}}$ disappearance — radioactive sources [?];
- $\bar{\nu}_e \rightarrow \bar{\nu}_{\text{other}}$ disappearance — reactor experiments [?].

None are entirely convincing, either individually or combined. However, there may be something very very interesting going on here...

What is Going on Here?

- Are these “anomalies” related?
- Is this neutrino oscillations, other new physics, or something else?
- Are these related to the origin of neutrino masses and lepton mixing?
- How do clear this up **definitively**?

Need new clever experiments, of the short-baseline type (and we are working on it)!

Observable wish list:

- ν_μ disappearance (and antineutrino);
- ν_e disappearance (and antineutrino);
- $\nu_\mu \leftrightarrow \nu_e$ appearance;
- $\nu_{\mu,e} \rightarrow \nu_\tau$ appearance.

If the oscillation interpretation of the short-baseline anomalies turns out to be correct ...

- We would have found new particle(s)!!!!!! [cannot overemphasize this!]
- Lots of Questions! What is it? Who ordered that? Is it related to the origin of neutrino masses? Is it related to dark matter?
- Lots of Work to do! Discovery, beyond reasonable doubt, will be followed by a panacea of new oscillation experiments. If, for example, there were one extra neutrino state the 4×4 mixing matrix would require three more mixing angles and three more CP-odd phases. Incredibly challenging. For example, two of the three CP-odd parameters, to zeroth order, can only be “seen” in tau-appearance.

...End Aside]

Do Neutrinos Decay?

Now that neutrinos have mass, the heavier neutrino mass eigenstates are unstable and will eventually decay into the lightest mass eigenstates plus X . In the new SM, X are photons and other light (anti)neutrinos.

$\nu_i \rightarrow \nu_j \gamma$ happens at the one-loop level, and expectations for τ are absurdly long: $\tau > 10^{37}$ years, for $m_\nu \sim 1$ eV (GIM suppressed).

Other new SM induced decays are also rare beyond all reason:

$$\tau_{\nu \rightarrow 3\nu} > 10^{38} \text{ years}$$

Constraints on the neutrino magnetic moment μ also severely constrain neutrino lifetimes *e.g.*,

$$\tau > 5 \times 10^{11} \left(\frac{10^{-10} \mu_B}{\mu_\nu} \right)^2 \text{ years} \quad m_\nu \sim 1 \text{ eV}$$

Observable neutrino decays are a sign for physics beyond the new SM. The new physics effects are either of the “bread and butter” $1/M_{\text{new}}$ -type, or involve the presence of very light, yet to be observed degrees of freedom (say, (quasi-)massless (pseudo)scalars, like “Majorons”).

Experimental bounds are very dependent on the decay mode (and the kinematics of the decay) and vary from the billion of years scale (bounds on UV light) to the hundreds of picoseconds scale (neutrinos from the atmosphere).

Best “model independent” bound come from a variety of sources. Lorentz invariance dictates that

$$\nu_i(t) = \nu_i(0)e^{-d_i L/E}$$

where $d_i \equiv \Gamma_i m_i = m_i/\tau_i$ and have dimensions of mass-squared.

These are relevant when, **just like the mass-squared differences in oscillations**, roughly

$$\Gamma_i m_i \frac{L}{E} \equiv d_i \frac{L}{E} = 5.07 \left(\frac{d_i}{\text{eV}^2} \right) \left(\frac{L}{\text{km}} \right) \left(\frac{\text{GeV}}{E} \right) > 1.$$

[NOTE: neutrinos are always heavily boosted, so the bounds are always less impressive than they appear. E.g., for neutrinos coming from the Sun

$$\gamma\tau > 500 \text{ s} \Rightarrow \tau > 500 \text{ s} \frac{m}{E} \sim 10^{-4} \text{ s} \left(\frac{m}{\text{eV}} \right) \left(\frac{5 \text{ MeV}}{E} \right)$$

]

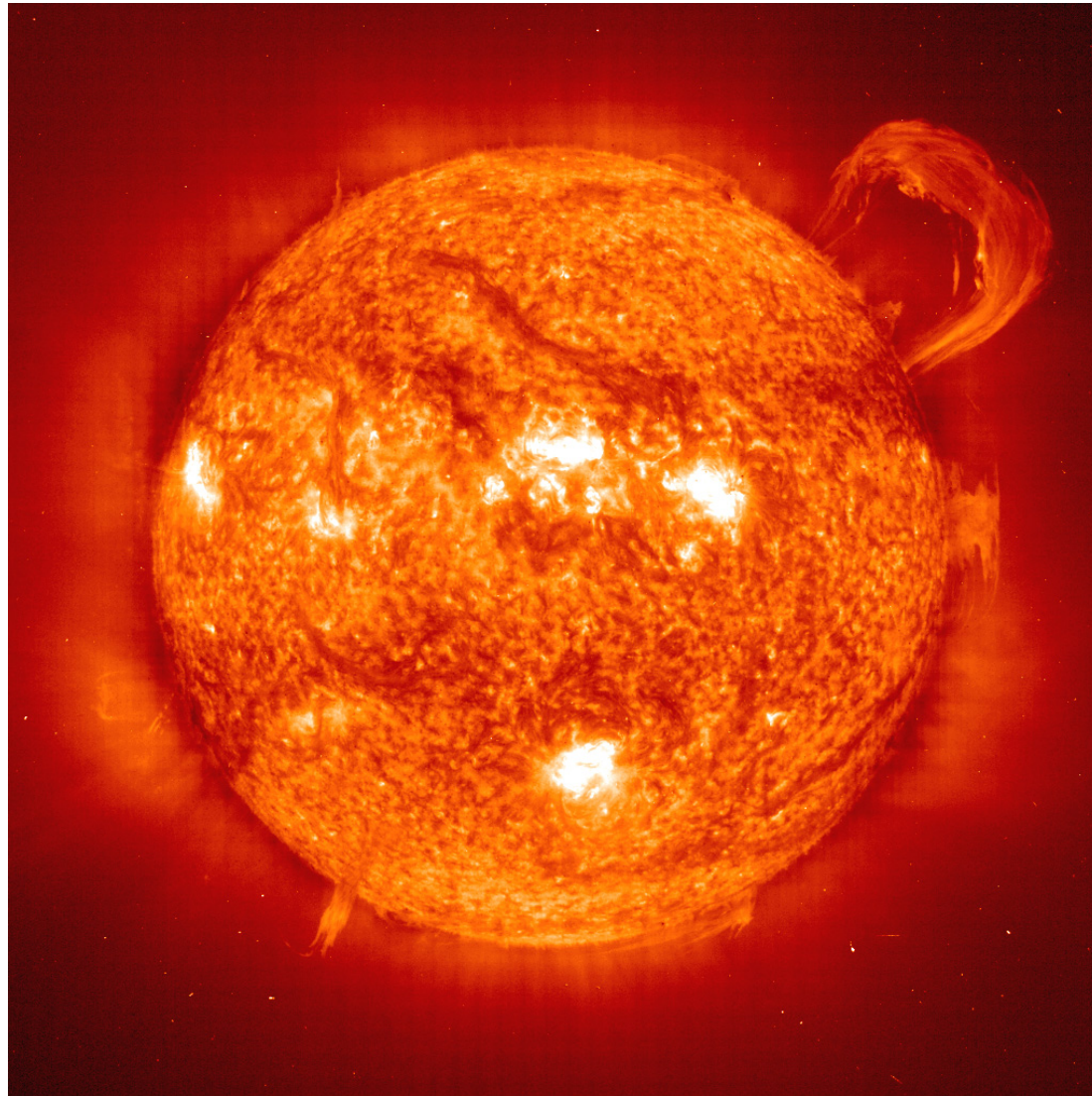
Best bounds come from experiments with very long baselines. Including.

- Atmospheric neutrinos. Constraints mostly $d_3 < 10^{-5} \text{ eV}^2$, for $d_{1,2} \ll d_3$.
- MINOS: $d_3 < 1.2 \times 10^{-4} \text{ eV}^2$, for $d_{1,2} \ll d_3$.
- SN1987A constraints one of the d_i to be tiny, $d_i < 1.2 \times 10^{-21} \text{ eV}^2$.
- There are also very strong bounds from ultra-high-energy neutrinos, now detected with Ice-Cube (very large boosts, but also very long distances).
- Big-Bang neutrinos. Bounds? May be circumventable with the right model ...



We got some of these neutrinos. At least one of the three mass-eigenstates is very long lived.

Neutrinos from the Sun: Abundant and Far

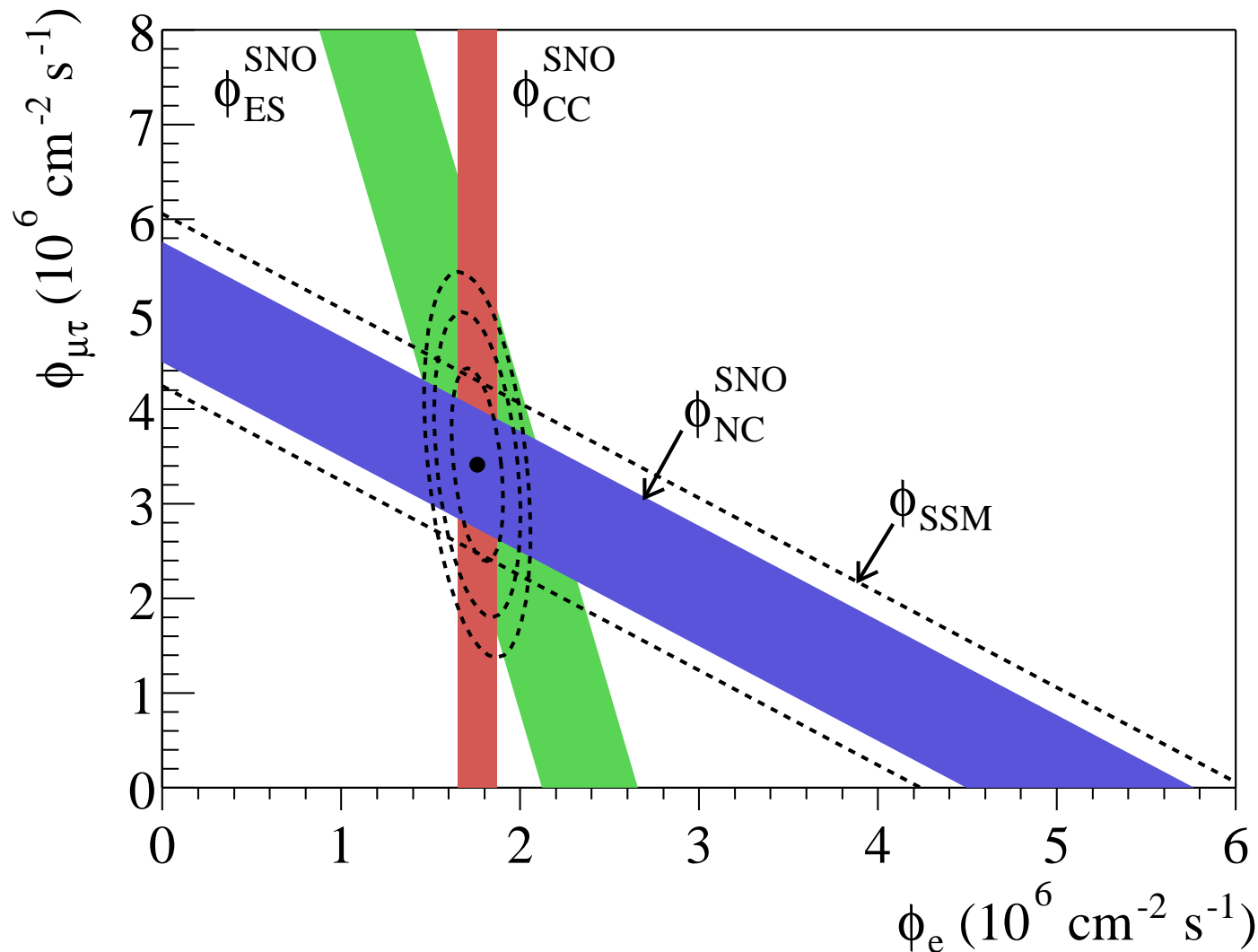


Reaction	Termination (%)	Neutrino Energy (MeV)
$p + p \rightarrow {}^2\text{H} + e^+ + \nu_e$	99.96	< 0.423
$p + e^- + p \rightarrow {}^2\text{H} + \nu_e$	0.044	1.445
${}^2\text{H} + p \rightarrow {}^3\text{He} + \gamma$	100	—
${}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + p + p$	85	—
${}^3\text{He} + {}^4\text{He} \rightarrow {}^7\text{Be} + \gamma$	15	—
${}^7\text{Be} + e^- \rightarrow {}^7\text{Li} + \nu_e$	15	0.863(90%) 0.386(10%)
${}^7\text{Li} + p \rightarrow {}^4\text{He} + {}^4\text{He}$		—
${}^7\text{Be} + p \rightarrow {}^8\text{B} + \gamma$	0.02	—
${}^8\text{B} \rightarrow {}^8\text{Be}^* + e^+ + \nu_e$		< 15
${}^8\text{Be} \rightarrow {}^4\text{He} + {}^4\text{He}$		—
${}^3\text{He} + p \rightarrow {}^4\text{He} + e^+ + \nu_e$	0.00003	< 18.8

Note: Adapted from Ref. 12. Please refer to Ref. 12 for a more detailed description.

around 100 billion go through
your thumb every second!

The SNO Experiment: conclusive evidence for flavor change



SNO Measures:

$$[CC] \quad \nu_e + {}^2\text{H} \rightarrow p + p + e^-$$

$$[ES] \quad \nu + e^- \rightarrow \nu + e^-$$

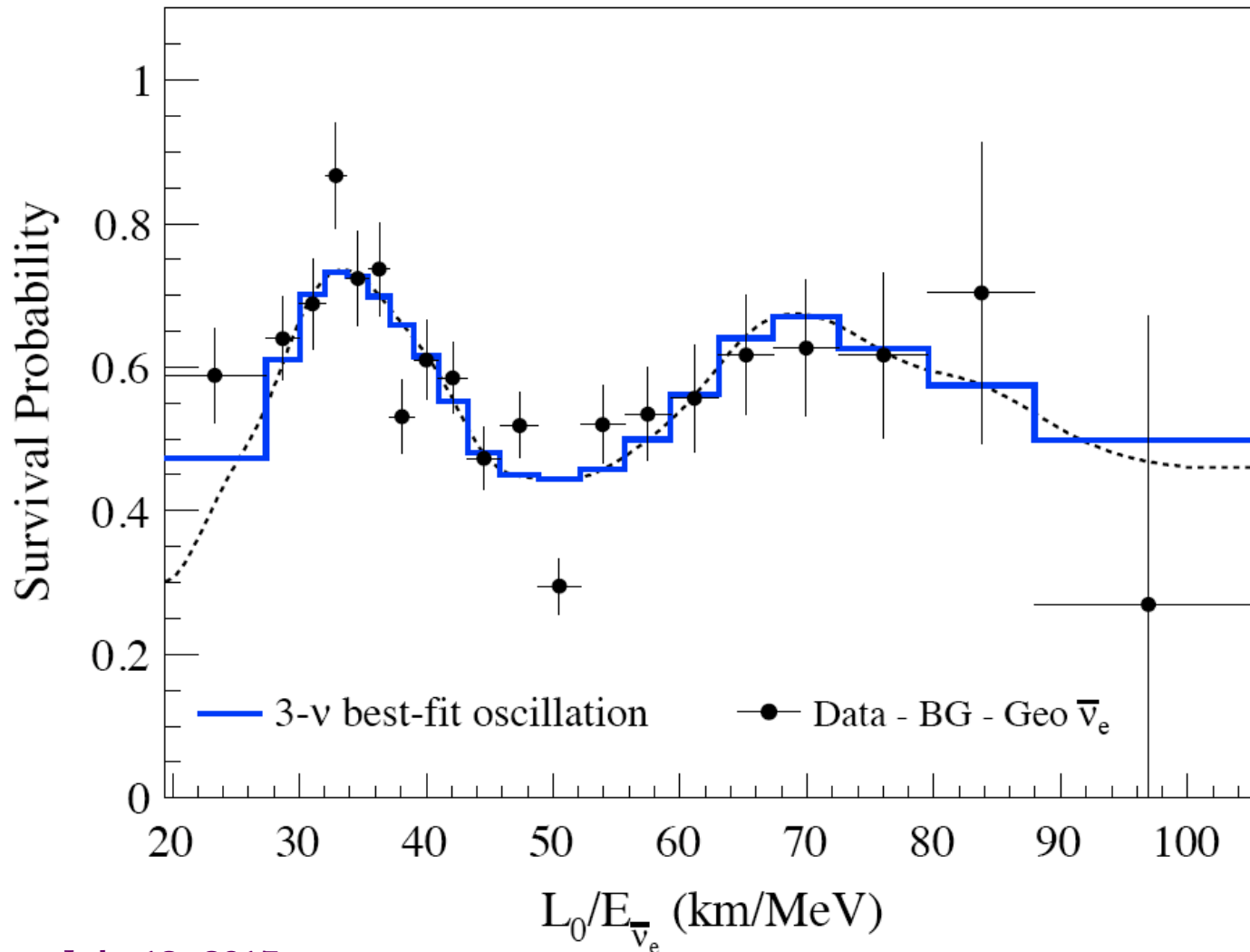
$$[NC] \quad \nu + {}^2\text{H} \rightarrow p + n + \nu$$

different reactions
sensitive to different
neutrino flavors.

Solar oscillations confirmed by Reactor experiment: KamLAND

[arXiv:1303.4667]

$$\text{phase} = 1.27 \left(\frac{\Delta m^2}{5 \times 10^{-5} \text{ eV}^2} \right) \left(\frac{5 \text{ MeV}}{E} \right) \left(\frac{L}{100 \text{ km}} \right)$$



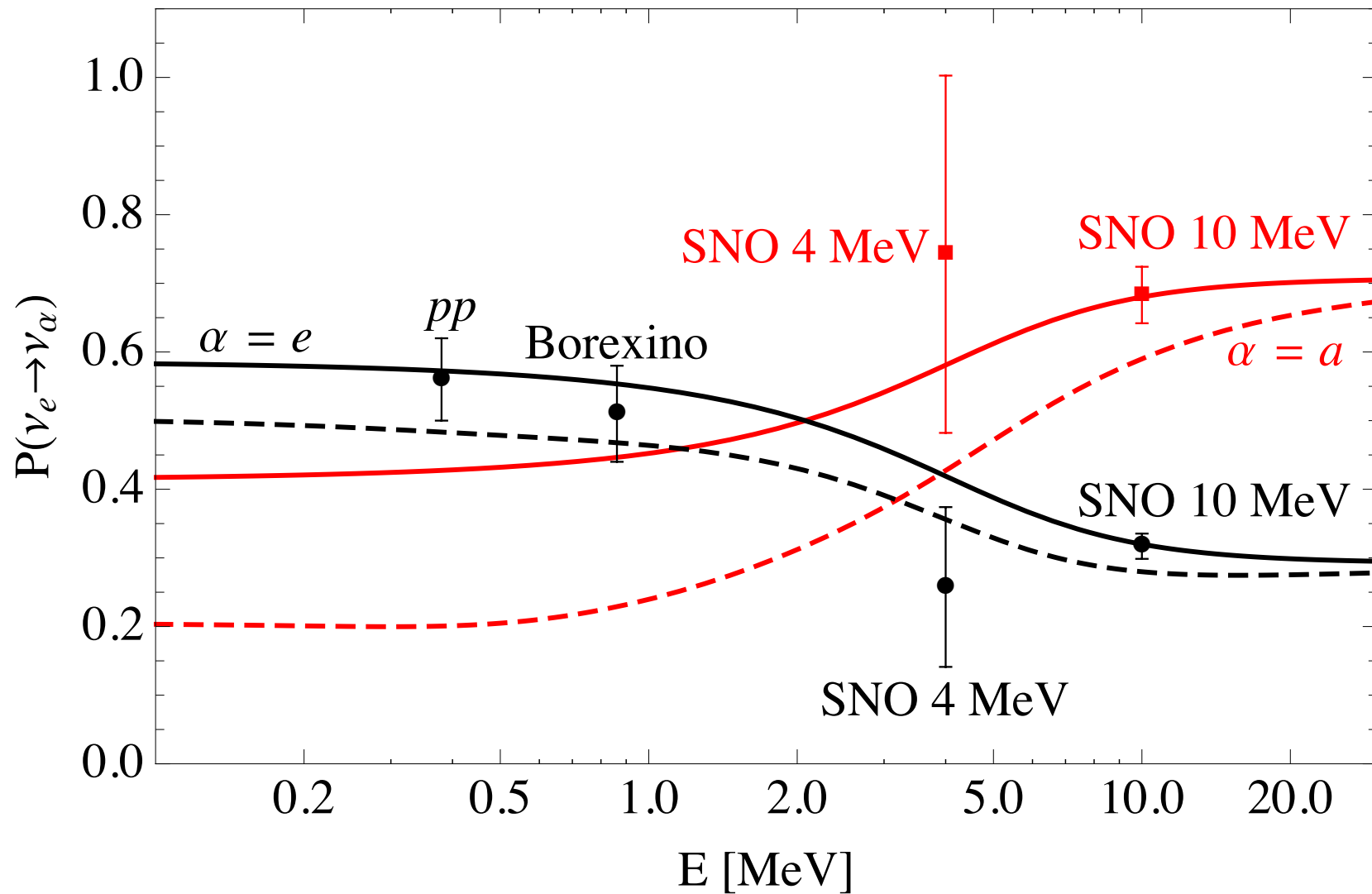
$$P_{ee} = 1 - \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

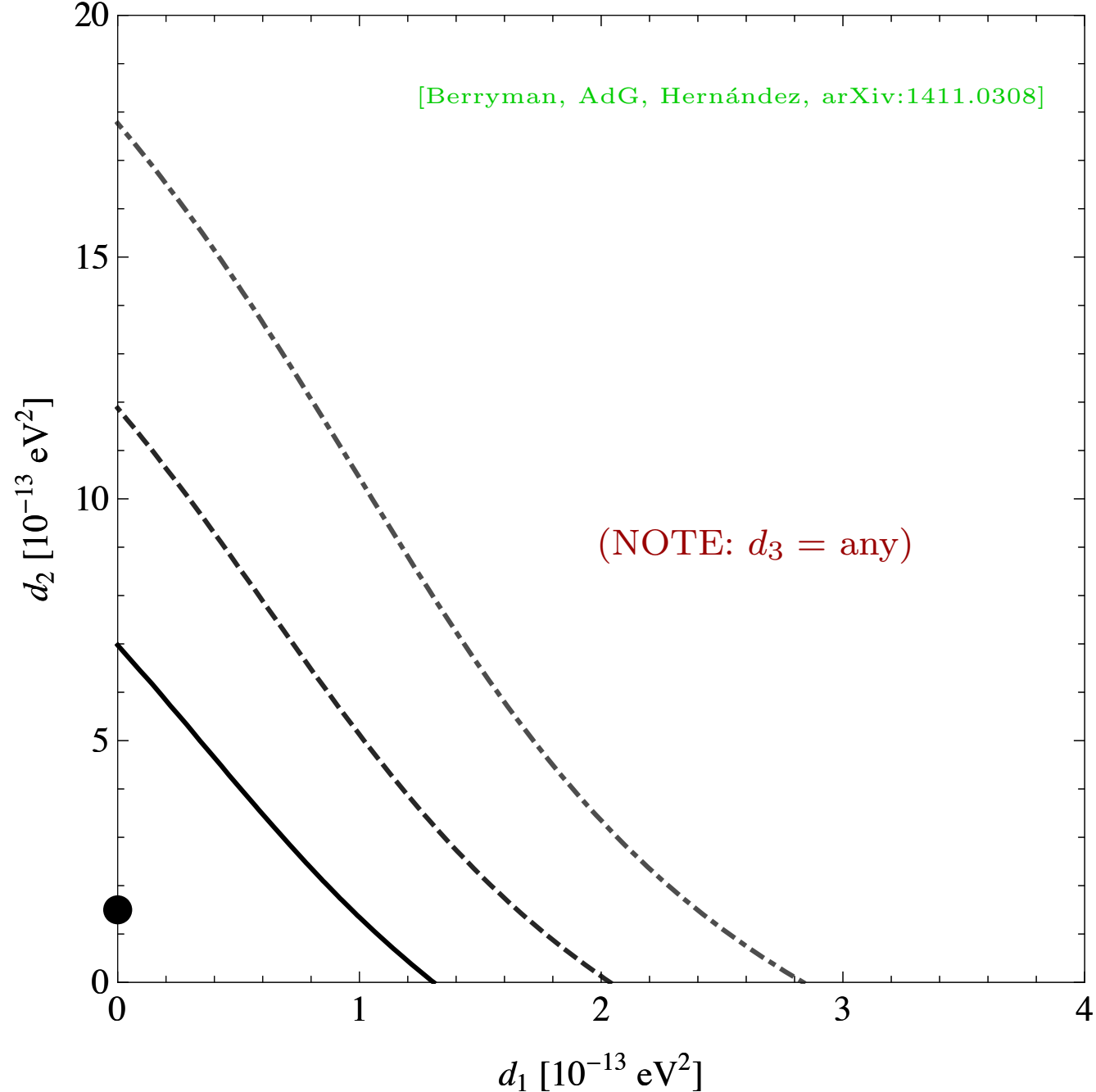
oscillatory behavior!

What Do We Know About the Massive Solar Neutrinos?

- They are an incoherent mixture of the three mass eigenstates, ν_1, ν_2, ν_3 . This is because of matter effects in the center of the Sun, combined with the fact that the mass-squared differences are “large.”
- The linear combinations depend on the solar neutrino energy. High energy solar neutrinos (^8B) are more than 90% ν_2 , while low energy ones (pp, ^7Be) are 70% ν_1 , 30% ν_2 . The ν_3 fraction is always very small (of order $\sin^2 \theta_{13} \sim 0.02$).
- This is great for determining the neutrino lifetime. For example, SNO measures mostly ν_2 and has been used to set a bound on the ν_2 lifetime in a two-flavor scenario [Beacom and Bell, hep-ph/0204111].
- Borexino provides a real-time measurement of the ^7Be neutrinos. Combining everything (plus $\sin^2 \theta_{13}$ is very small), it is possible to place more-or-less model-independent bounds on the lifetimes of the three neutrino mass eigenstates [Berryman, AdG, Hernández, arXiv:1411.0308].

solid: $d_1 = d_2 = 0$. Dashed: $d_2 = 2 \times 10^{-12} \text{ eV}^2$.





Are There More Neutrinos?

If there are more neutrinos with a well-defined mass, it is easy to extend the Paradigm:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_? \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} & \cdots \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} & \cdots \\ U_{?1} & U_{?2} & U_{?3} & U_{?4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \vdots \end{pmatrix}$$

- New mass eigenstates easy: ν_4 with mass m_4 , ν_5 with mass m_5 , etc.
- What are these new “flavor” (or weak) eigenstates $\nu_?$?

Number from e^+e^- Colliders

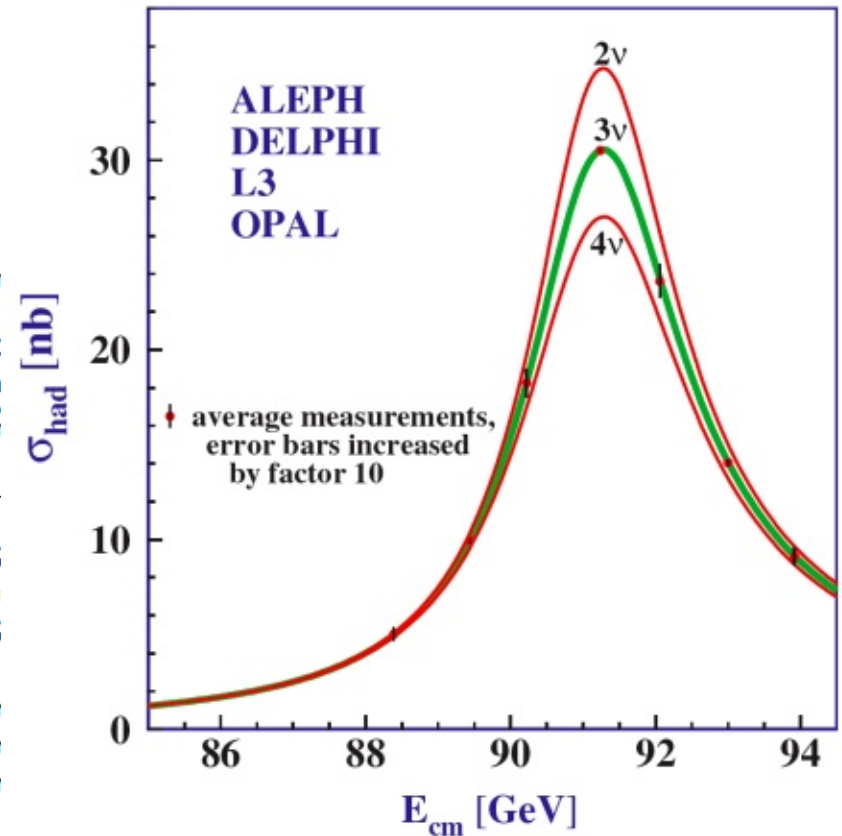
Number of Light ν Types

VALUE	DOCUMENT ID	TECN
2.9840 ± 0.0082	¹ LEP-SLC	06 RVUE
• • • We do not use the following data for averages, fits, limits, etc. • • •		
3.00 ± 0.05	² LEP	92 RVUE
¹ Combined fit from ALEPH, DELPHI, L3 and OPAL Experiments.		
² Simultaneous fits to all measured cross section data from all four LEP experimer		

Number of Light ν Types from Direct Measurement of Invisible Z Width

In the following, the invisible Z width is obtained from studies of single-photon from the reaction $e^+e^- \rightarrow \nu\bar{\nu}\gamma$. All are obtained from LEP runs in the E_{cm}^{ee} 88–209 GeV.

VALUE	DOCUMENT ID	TECN	COMMENT
2.92 ± 0.05 OUR AVERAGE	Error includes scale factor of 1.2.		
$2.84 \pm 0.10 \pm 0.14$	ABDALLAH	05B DLPH	$\sqrt{s} = 180\text{--}209$ G
$2.98 \pm 0.05 \pm 0.04$	ACHARD	04E L3	1990–2000 LEP r
2.86 ± 0.09	HEISTER	03C ALEP	$\sqrt{s} = 189\text{--}209$ G
$2.69 \pm 0.13 \pm 0.11$	ABBIENDI,G	00D OPAL	1998 LEP run
$2.89 \pm 0.32 \pm 0.19$	ABREU	97J DLPH	1993–1994 LEP r
$3.23 \pm 0.16 \pm 0.10$	AKERS	95C OPAL	1990–1992 LEP r
$2.68 \pm 0.20 \pm 0.20$	BUSKULIC	93L ALEP	1990–1991 LEP r
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$2.84 \pm 0.15 \pm 0.14$	ABREU	00Z DLPH	1997–1998 LEP runs
3.01 ± 0.08	ACCIARRI	99R L3	1991–1998 LEP runs
$3.1 \pm 0.6 \pm 0.1$	ADAM	96C DLPH	$\sqrt{s} = 130, 136$ GeV



Limits from Astrophysics and Cosmology

Number of Light ν Types

("light" means $<$ about 1 MeV). See also OLIVE 81. For a review of limits based on Nucleosynthesis, Supernovae, and also on terrestrial experiments, see DENEGR 90. Also see "Big-Bang Nucleosynthesis" in this Review.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 4.10	95	³ MORESCO	12 COSM	

New neutrinos don't couple to the Z-boson if they are light (~ 45 GeV)

Hence STERILE neutrinos

I'll concentrate on “pure” sterile neutrinos (no other interactions with anyone). Such states only interact with the SM via weak mixing with the active neutrinos we know and love.

There are many theoretical complaints related to light sterile neutrinos:

- Who ordered that? What are sterile neutrinos good for?
- Why would they be light? Sterile neutrinos are “theoretically expected” to be very heavy...
- If there are sterile neutrinos, can we say anything about their properties? Say, is the sterile–active neutrino mixing angle calculable? Are there preferred regions of the sterile neutrino parameter space?
- ...

BOTTOM LINE: In spite of theoretical complaints, sterile neutrinos are a viable logical possibility. They are experimentally constrained, but are certainly allowed. They do not depend on whether neutrinos are Majorana or Dirac, do not imply the existence of more charged leptons (or quarks), do not lead to theoretical inconsistencies (anomalies), etc.

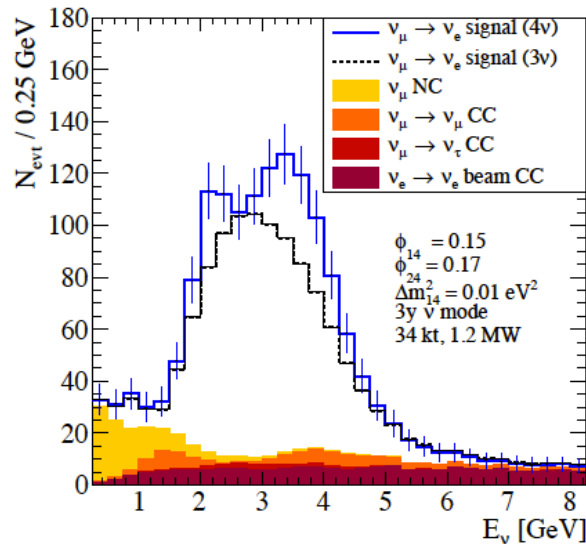
$$\begin{aligned}
U_{e2} &= s_{12}c_{13}c_{14}, \\
U_{e3} &= e^{-i\eta_1} s_{13}c_{14}, \\
U_{e4} &= e^{-i\eta_2} s_{14}, \\
U_{\mu 2} &= c_{24} (c_{12}c_{23} - e^{i\eta_1} s_{12}s_{13}s_{23}) - e^{i(\eta_2-\eta_3)} s_{12}s_{14}s_{24}c_{13}, \\
U_{\mu 3} &= s_{23}c_{13}c_{24} - e^{i(\eta_2-\eta_3-\eta_1)} s_{13}s_{14}s_{24}, \\
U_{\mu 4} &= e^{-i\eta_3} s_{24}c_{14}, \\
U_{\tau 2} &= c_{34} (-c_{12}s_{23} - e^{i\eta_1} s_{12}s_{13}c_{23}) - e^{i\eta_2} c_{13}c_{24}s_{12}s_{14}s_{34} \\
&\quad - e^{i\eta_3} (c_{12}c_{23} - e^{i\eta_1} s_{12}s_{13}s_{23}) s_{24}s_{34}, \\
U_{\tau 3} &= c_{13}c_{23}c_{34} - e^{i(\eta_2-\eta_1)} s_{13}s_{14}s_{34}c_{24} - e^{i\eta_3} s_{23}s_{24}s_{34}c_{13}, \\
U_{\tau 4} &= s_{34}c_{14}c_{24}.
\end{aligned}$$

When the new mixing angles ϕ_{14} , ϕ_{24} , and ϕ_{34} vanish, one encounters oscillations among only three neutrinos, and we can map the remaining parameters $\{\phi_{12}, \phi_{13}, \phi_{23}, \eta_1\} \rightarrow \{\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}\}$.

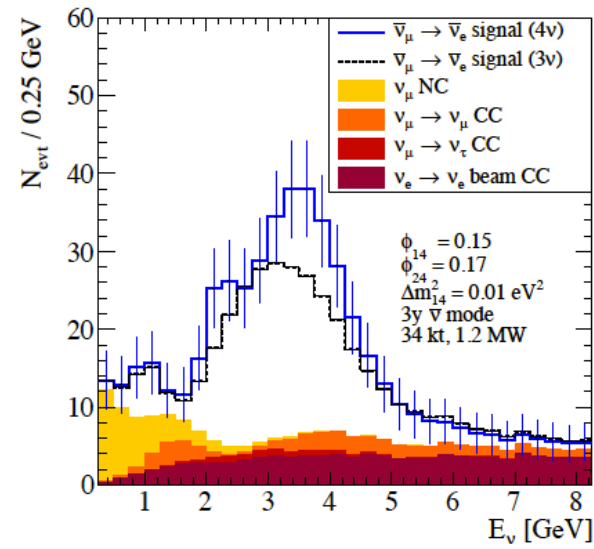
Also

$$\eta_s \equiv \eta_2 - \eta_3,$$

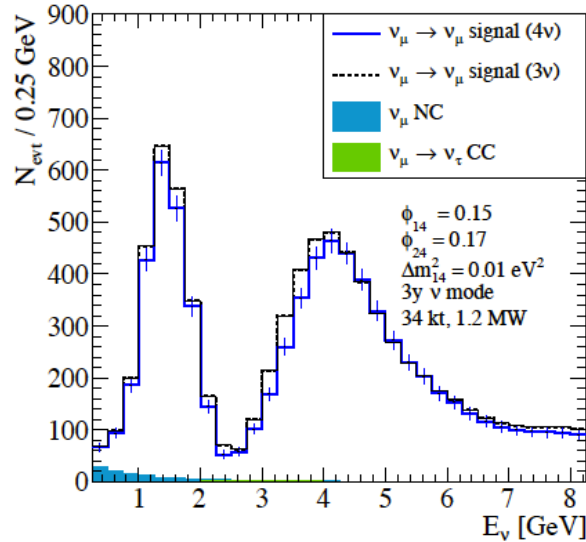
is the only new CP-odd parameter to which oscillations among ν_e and ν_μ are sensitive.



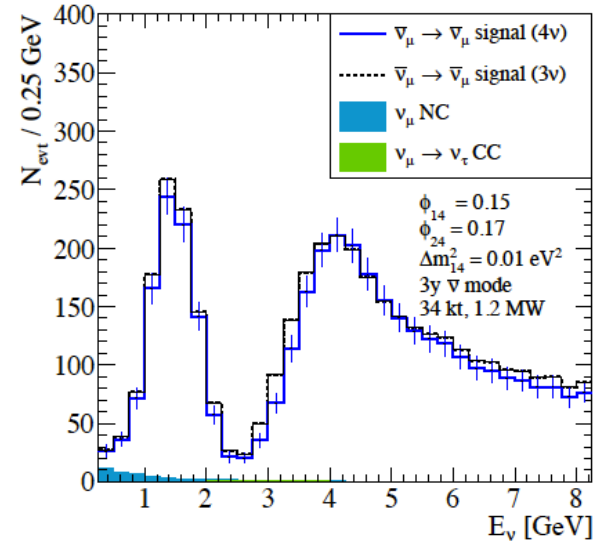
(a)



(b)



(c)



(d)

[Berryman et al, arXiv:1507.03986]

FIG. 1: Expected signal and background yields for six years (3y ν + 3y $\bar{\nu}$) of data collection at DUNE, using fluxes projected by Ref. [1], for a 34 kiloton detector, and a 1.2 MW beam. (a) and (b) show appearance channel yields for neutrino and antineutrino beams, respectively, while (c) and (d) show disappearance channel yields. The 3 ν signal corresponds to the standard three-neutrino hypothesis, where $\sin^2 \theta_{12} = 0.308$, $\sin^2 \theta_{13} = 0.0235$, $\sin^2 \theta_{23} = 0.437$, $\Delta m_{12}^2 = 7.54 \times 10^{-5} \text{ eV}^2$, $\Delta m_{13}^2 = 2.43 \times 10^{-3} \text{ eV}^2$, $\delta_{CP} = 0$, while the 4 ν signal corresponds to $\sin^2 \phi_{12} = 0.315$, $\sin^2 \phi_{13} = 0.024$, $\sin^2 \phi_{23} = 0.456$, $\sin^2 \phi_{14} = 0.023$, $\sin^2 \phi_{24} = 0.030$, $\Delta m_{14}^2 = 10^{-2} \text{ eV}^2$, $\eta_1 = 0$, and $\eta_s = 0$. Statistical uncertainties are shown as vertical bars in each bin. Backgrounds are defined in the text and are assumed to be identical for the three- and four-neutrino scenarios: any discrepancy is negligible after accounting for a 5% normalization uncertainty.

Non-Standard Neutrino Interactions (NSI)

(AdG and Kelly, arXiv:1511.05562)

Effective Lagrangian:

$$\mathcal{L}^{\text{NSI}} = -2\sqrt{2}G_F(\bar{\nu}_\alpha\gamma_\rho\nu_\beta) \sum_{f=e,u,d} (\epsilon_{\alpha\beta}^{fL}\bar{f}_L\gamma^\rho f_L + \epsilon_{\alpha\beta}^{fR}\bar{f}_R\gamma^\rho f_R) + h.c.,$$

For oscillations,

$$H_{ij} = \frac{1}{2E_\nu} \text{diag}\{0, \Delta m_{12}^2, \Delta m_{13}^2\} + V_{ij},$$

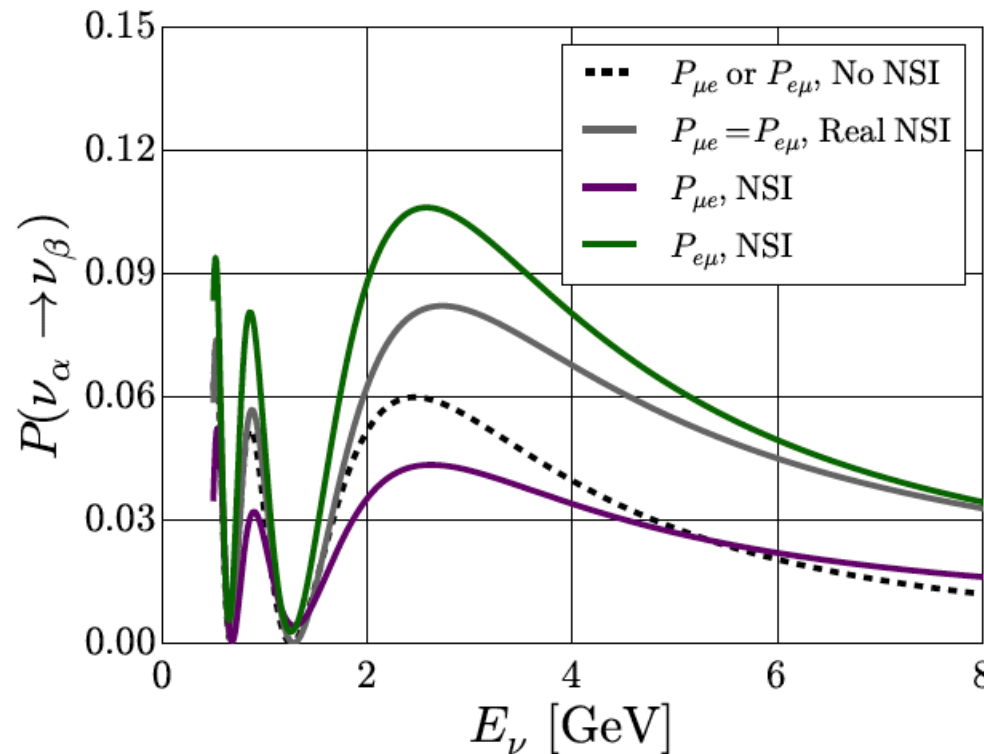
where

$$V_{ij} = U_{i\alpha}^\dagger V_{\alpha\beta} U_{\beta j},$$

$$V_{\alpha\beta} = A \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix},$$

$A = \sqrt{2}G_F n_e$. $\epsilon_{\alpha\beta}$ are linear combinations of the $\epsilon_{\alpha\beta}^{fL,R}$. Important: Propagation effects only. We don't include NSI effects in production or detection.

There are new sources of CP-invariance violation! [easier to see T-invariance violation]



[AdG and Kelly, arXiv:1511.05562]

FIG. 2: T -invariance violating effects of NSI at $L = 1300$ km for $\epsilon_{e\mu} = 0.1e^{i\pi/3}$, $\epsilon_{e\tau} = 0.1e^{-i\pi/4}$, $\epsilon_{\mu\tau} = 0.1$ (all other NSI parameters are set to zero). Here, the three-neutrino oscillation parameters are $\sin^2 \theta_{12} = 0.308$, $\sin^2 \theta_{13} = 0.0234$, $\sin^2 \theta_{23} = 0.437$, $\Delta m_{12}^2 = 7.54 \times 10^{-5}$ eV², $\Delta m_{13}^2 = 2.47 \times 10^{-3}$ eV², and $\delta = 0$, i.e., no “standard” T -invariance violation. The green curve corresponds to $P_{e\mu}$ while the purple curve corresponds to $P_{\mu e}$. If, instead, all non-zero NSI are real ($\epsilon_{e\mu} = 0.1$, $\epsilon_{e\tau} = 0.1$, $\epsilon_{\mu\tau} = 0.1$), $P_{e\mu} = P_{\mu e}$, the grey curve. The dashed line corresponds to the pure three-neutrino oscillation probabilities assuming no T -invariance violation (all $\epsilon_{\alpha\beta} = 0$, $\delta = 0$).

Do Neutrinos Couple to Photons?

Neutrinos have NO electric charge (hence their name). However, since they interact with charge particles via the weak interactions, they are expected to talk to photons “indirectly” (like, say, the neutron). That is guaranteed to happen, unless protected by a symmetry \rightarrow this is exactly what happens when neutrinos are massless!

Now that neutrinos have mass, they are “allowed” to have a nonzero magnetic moment μ_ν .

The nature of μ_ν will depend on whether the neutrino is its own antiparticle:

$$\mathcal{L}_{m.m.} = \mu_\nu^{ij} (\nu_i \sigma_{\mu\nu} \nu_j F^{\mu\nu}) + H.c.,$$

$$\mu_\nu^{ij} = -\mu_\nu^{ji}, \quad i, j = 1, 2, 3 \rightarrow \text{Majorana Magnetic Moment}$$

or

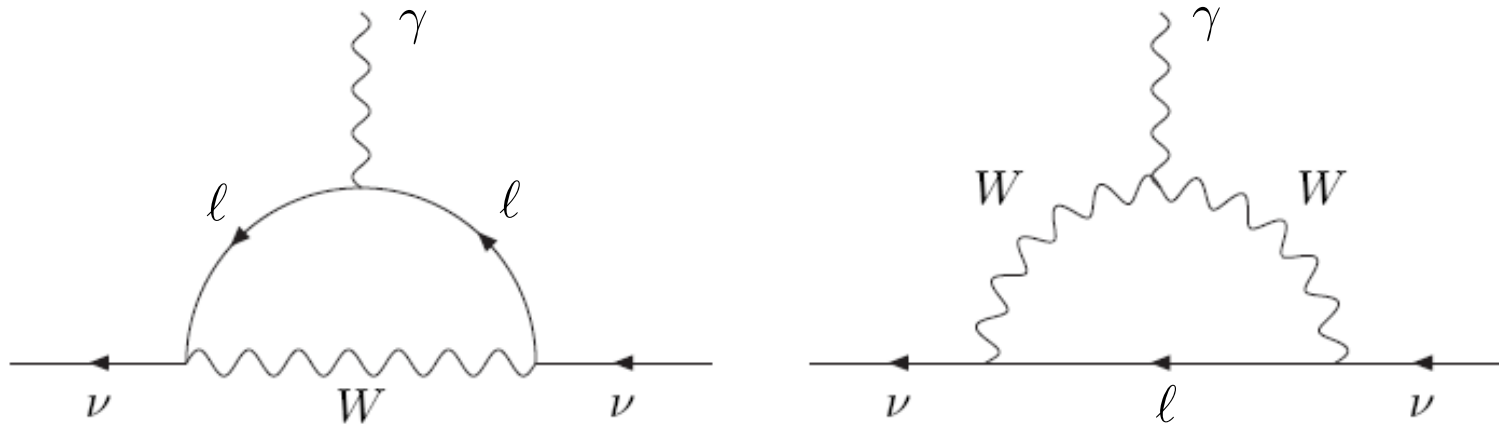
$$\mathcal{L}_{m.m.} = \mu_\nu^{ij} (\bar{\nu}_i \sigma_{\mu\nu} N F^{\mu\nu}) + H.c.,$$

$$i, j = 1, 2, 3 \rightarrow \text{Dirac Magnetic Moment}$$

in new SM, whether neutrinos are Majorana or Dirac fermions, μ is really small:

$$\mu_{ij} \leq \sum_{\alpha} U_{\alpha i} U_{\alpha j}^* \frac{3eG_F}{8\sqrt{2}\pi^2} m_{\nu} = 3 \times 10^{-20} \mu_B \left(\frac{m_{\nu}}{10^{-1} \text{ eV}} \right) \sum_{\alpha} U_{\alpha i} U_{\alpha j}^* \quad \left(\mu_B = \frac{e}{2m_e} \right)$$

[Dirac case]



Generic new, electroweak-scale physics effects yield much larger neutrino magnetic moments. *E.g.*,

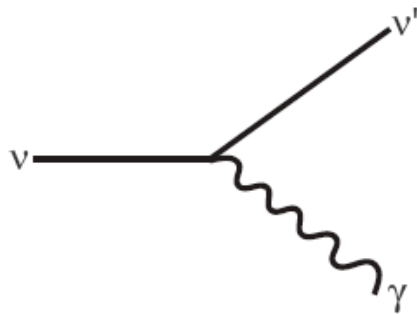
$$\mu \sim \frac{e\lambda^2}{M_{\text{new}}^2} m_f \qquad f = e, \mu, \tau, \dots$$

Searches for neutrino magnetic moments constrain the new physics scale (M) and coupling (λ) like searches for new physics in the charged-lepton sector: $\mu \rightarrow e\gamma$, $(g-2)_\mu$, muon and electron electric dipole moments, etc. After all, they all come from the same effective operator!

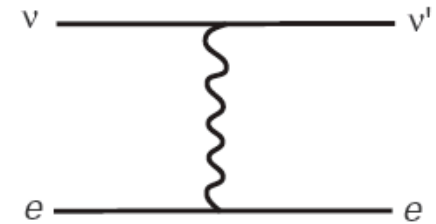
One can place bounds on (or find “evidence” for)

- SUSY,
- large extra dimensions ($\bar{\nu}_e e^- \rightarrow \sum_{\mathbf{k}} \bar{\nu}_{\mathbf{k}} e^-$),
- ... (the usual suspects).

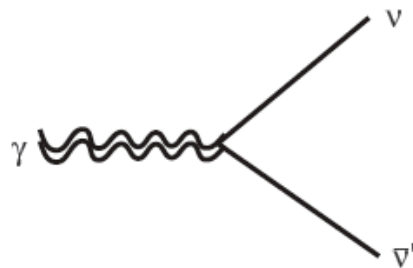
How To See the Neutrino and the Photon Interacting



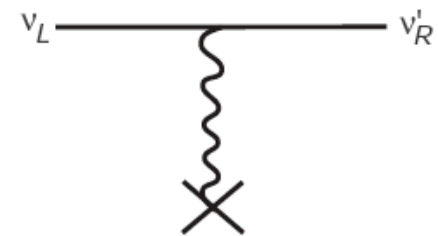
ν decay or Cherenkov radiation



$\nu - e$ scatt. or $e^+ - e^-$ annihilation



Plasmon decay



Spin (flavor) precession

Bounds come from a variety of sources and constrain different linear combinations of elements of μ_ν .

- $\bar{\nu}_e e^- \rightarrow \nu_\beta (\bar{\nu}_\beta) e^-, \forall \beta (\beta = e, \mu, \tau)$ **TEXONO, MUNU reactor expt's.**

$$\frac{d\sigma}{dT}(\bar{\nu}_e e \rightarrow \nu_x e) = \frac{2G_\mu^2 m_e}{\pi E_\nu^2} \left[(\sin^2 \theta_W)^2 E_\nu^2 + \left(\frac{1}{2} + \sin^2 \theta_W \right)^2 (E_\nu - T)^2 + \right. \\ \left. - \sin^2 \theta_W \left(\frac{1}{2} + \sin^2 \theta_W \right) m_e T \right] + \mu^2 \frac{\pi \alpha^2}{E_\nu m_e^2} \left(\frac{E_\nu}{T} - 1 \right),$$

where $\mu^2 = \sum_\alpha |\mu_{e\alpha}|^2$ is a particular combination of magnetic moments ($\mu_{\alpha\beta} = U_{\alpha i} \mu_{ij} U_{\beta j}^*$). T is the recoil electron kinetic energy, E_ν is the incoming neutrino energy.

- searches for electron antineutrinos from the Sun ($\nu_e^{(m.\overline{m}.)}$ $\bar{\nu}_\beta^{(\text{osc})}$ $\bar{\nu}_e$).
Applies only in the case of Majorana neutrinos.

Uncertainties: \vec{B} in the Sun (measure only μB)?, how well oscillation parameters are known?

KamLAND: $\Phi_{\bar{\nu}_e}^\odot < 2.8 \times 10^{-4} \Phi_{\nu_e}^{8\text{B}}$

- astrophysics red giants, SN1987A, ...

$$\Rightarrow \boxed{\mu_\nu < 1.5 \times 10^{-10} \mu_B} \quad (\text{PDG accepted bound});$$

also $O(10^{-[12 \div 11]})$ bounds from astrophysics and solar neutrinos.

In Conclusion

The venerable Standard Model sprung a leak in the end of the last century (and we are still trying to patch it): neutrinos are not massless!

1. We still **know very little** about the new physics uncovered by neutrino oscillations.
2. **neutrino masses are very small** – we don't know why, but we think it means something important.
3. **neutrino mixing is “weird”** – we don't know why, but we think it means something important. [I did not talk about this at all]

4. We **need more experimental input** These will come from a rich, diverse experimental program which relies heavily on the existence of underground facilities capable of hosting large detectors (**double-beta decay, precision neutrino oscillations, supernova neutrinos, proton decay, etc**).
5. Precision measurements of neutrino oscillations are sensitive to several new phenomena, including new neutrino properties, the existence of new states, or the existence of new interactions. There is a lot of work to be done when it comes to understanding which new phenomena can be probed in long-baseline oscillation experiments (and how well) and what are the other questions one can ask – related and unrelated to neutrinos – of these unique particle physics experiments.
6. There is plenty of **room for surprises**, as neutrinos are potentially very deep probes of all sorts of physical phenomena. Remember that neutrino oscillations are “quantum interference devices” – potentially very sensitive to whatever else may be out there (e.g., $\Lambda \simeq 10^{14}$ GeV).

Backup Slides . . .



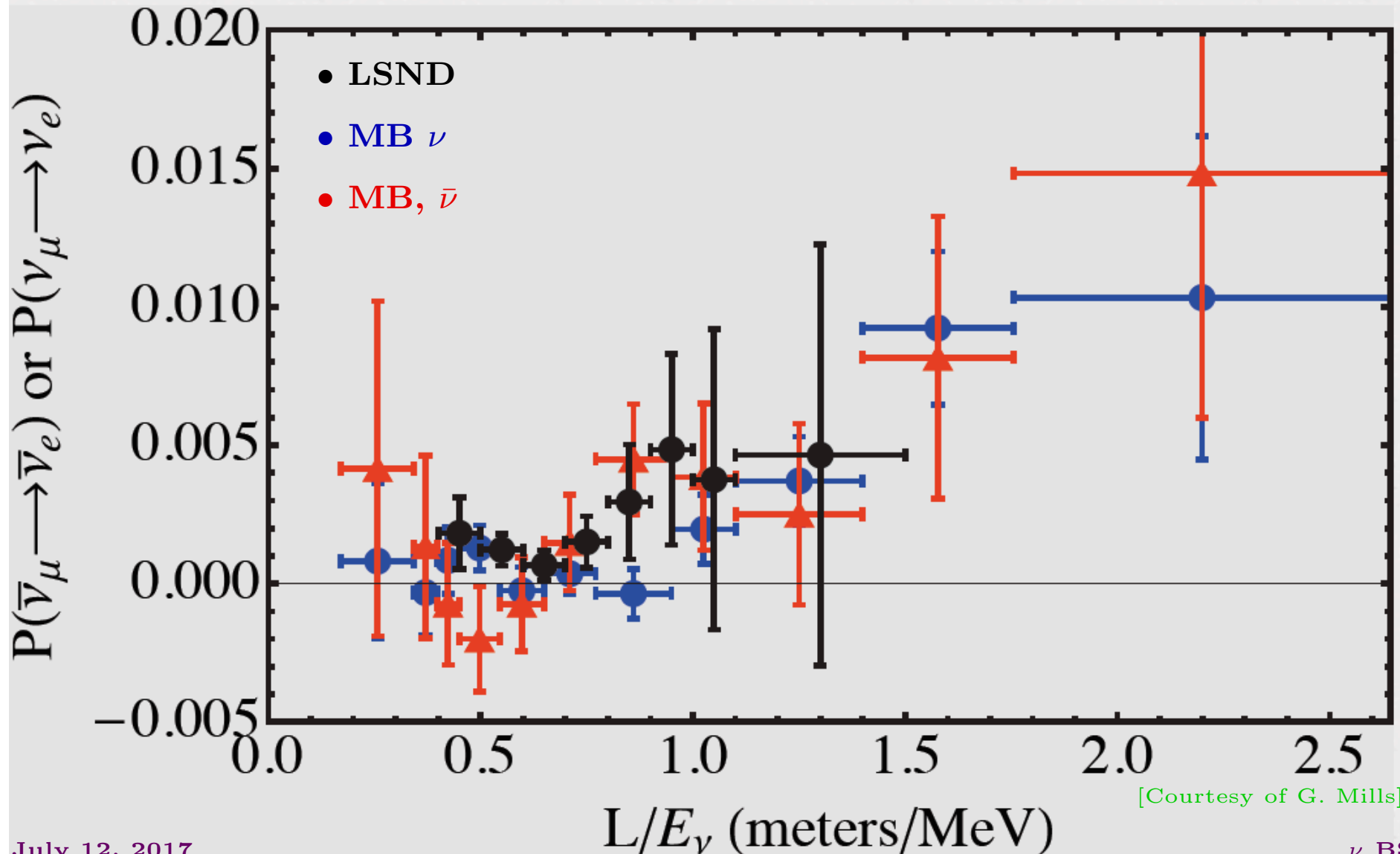
Not all is well(?): The Short Baseline Anomalies

Different data sets, sensitive to L/E values small enough that the known oscillation frequencies do not have “time” to operate, point to unexpected neutrino behavior. These include

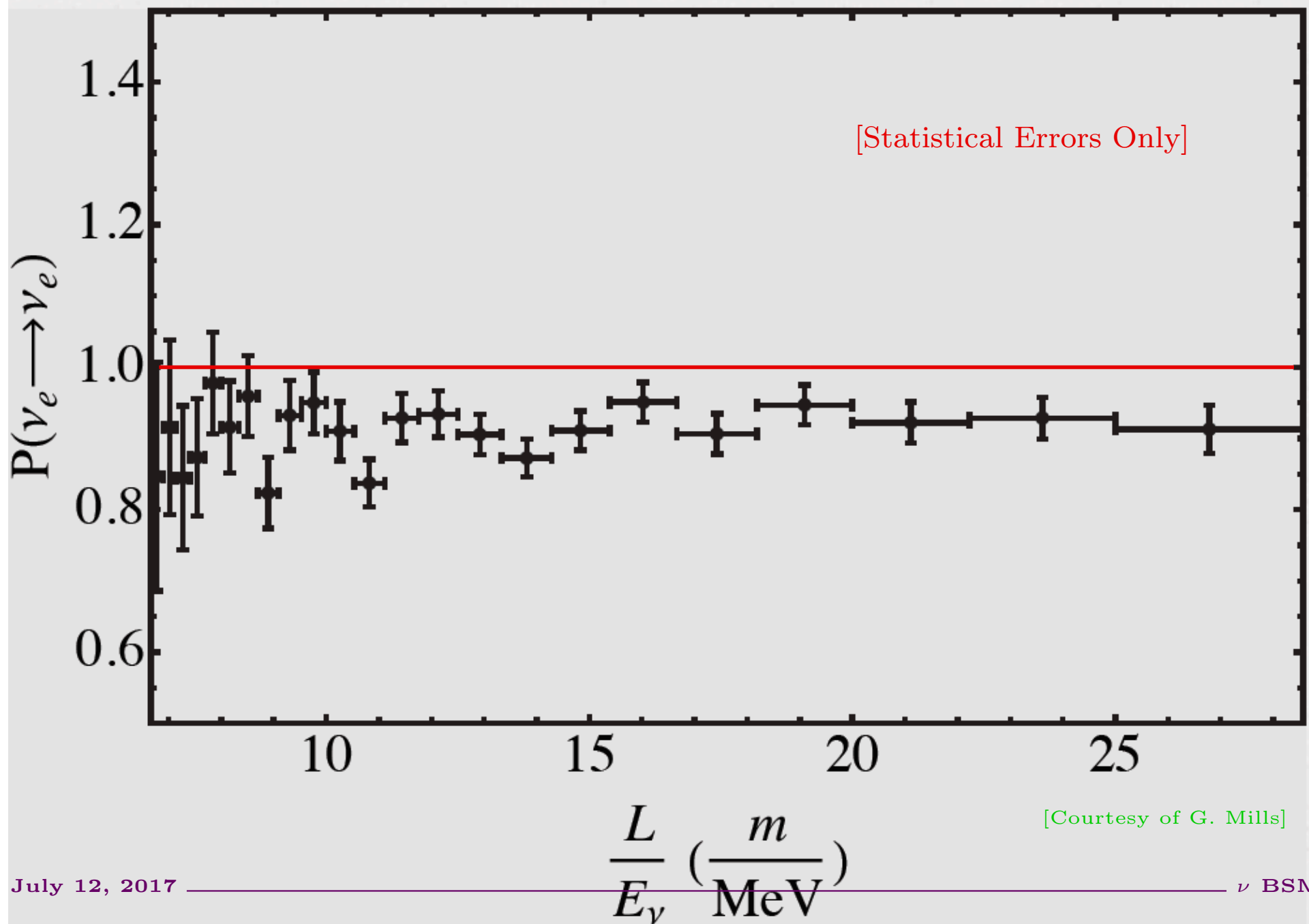
- $\nu_\mu \rightarrow \nu_e$ appearance — LSND, MiniBooNE;
- $\nu_e \rightarrow \nu_{\text{other}}$ disappearance — radioactive sources;
- $\bar{\nu}_e \rightarrow \bar{\nu}_{\text{other}}$ disappearance — reactor experiments.

None are entirely convincing, either individually or combined. However, there may be something very very interesting going on here...

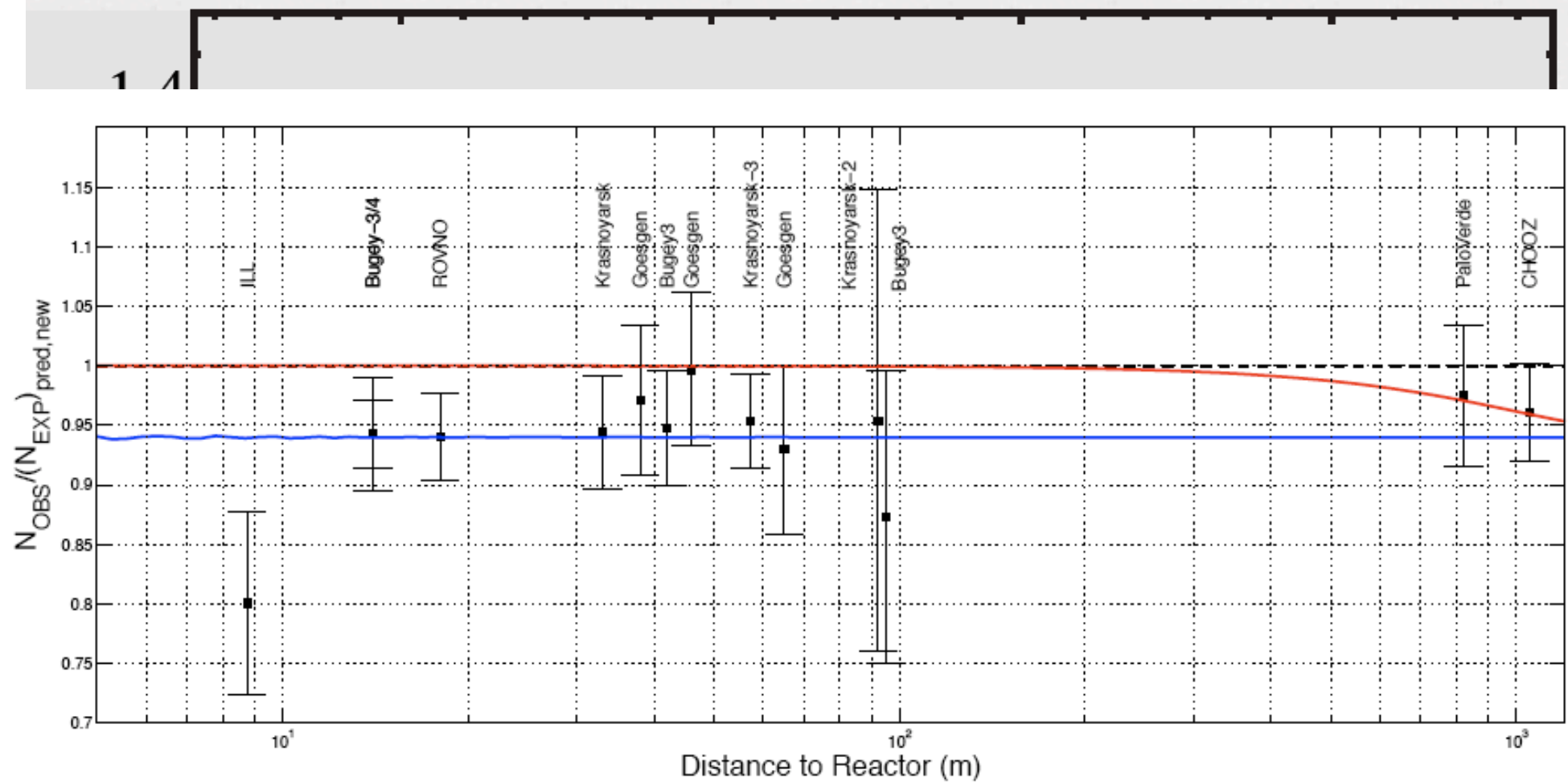
MiniBooNE & LSND



Bugey 40 m



Bugey 40 m



10

15

20

25

$$\frac{L}{E_\nu} \left(\frac{m}{\text{MeV}} \right)$$

What is Going on Here?

- Are these “anomalies” related?
- Is this neutrino oscillations, other new physics, or something else?
- Are these related to the origin of neutrino masses and lepton mixing?
- How do clear this up **definitively**?

Need new clever experiments, of the short-baseline type!

Observable wish list:

- ν_μ disappearance (and antineutrino);
- ν_e disappearance (and antineutrino);
- $\nu_\mu \leftrightarrow \nu_e$ appearance;
- $\nu_{\mu,e} \rightarrow \nu_\tau$ appearance.

Big Bang Neutrinos are Warm Dark Matter

Planck Collaboration: Cosmological parameters

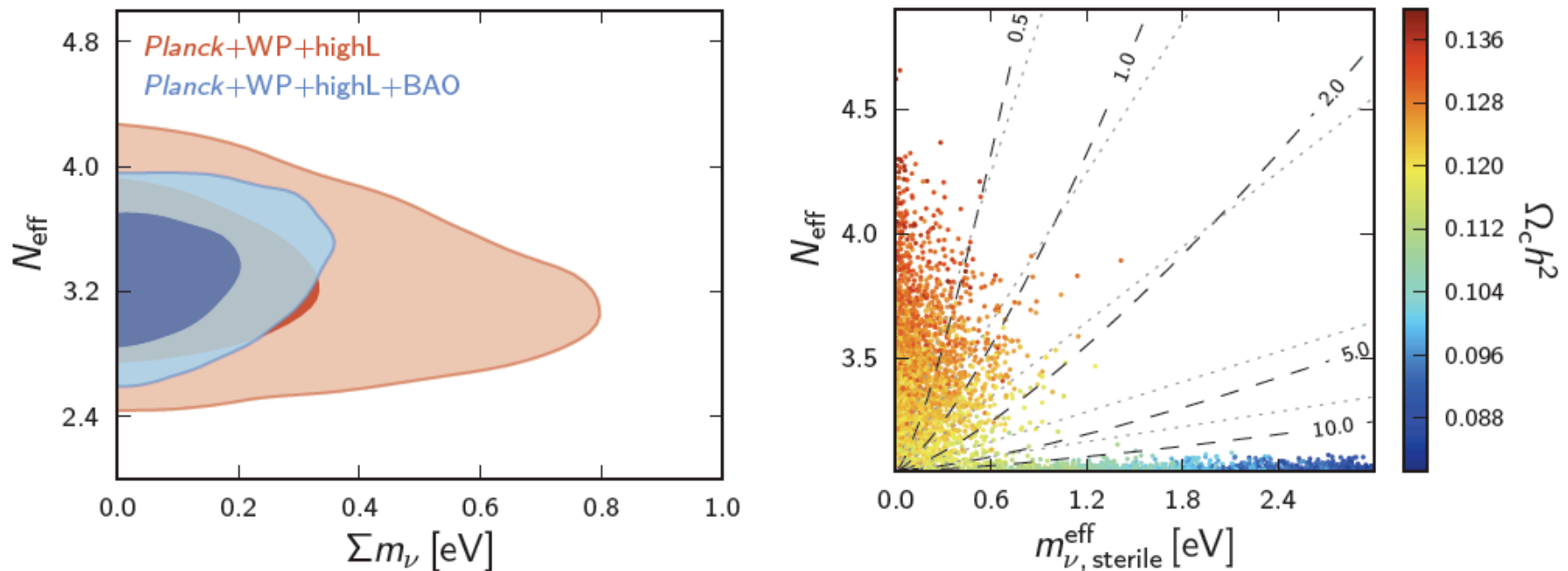
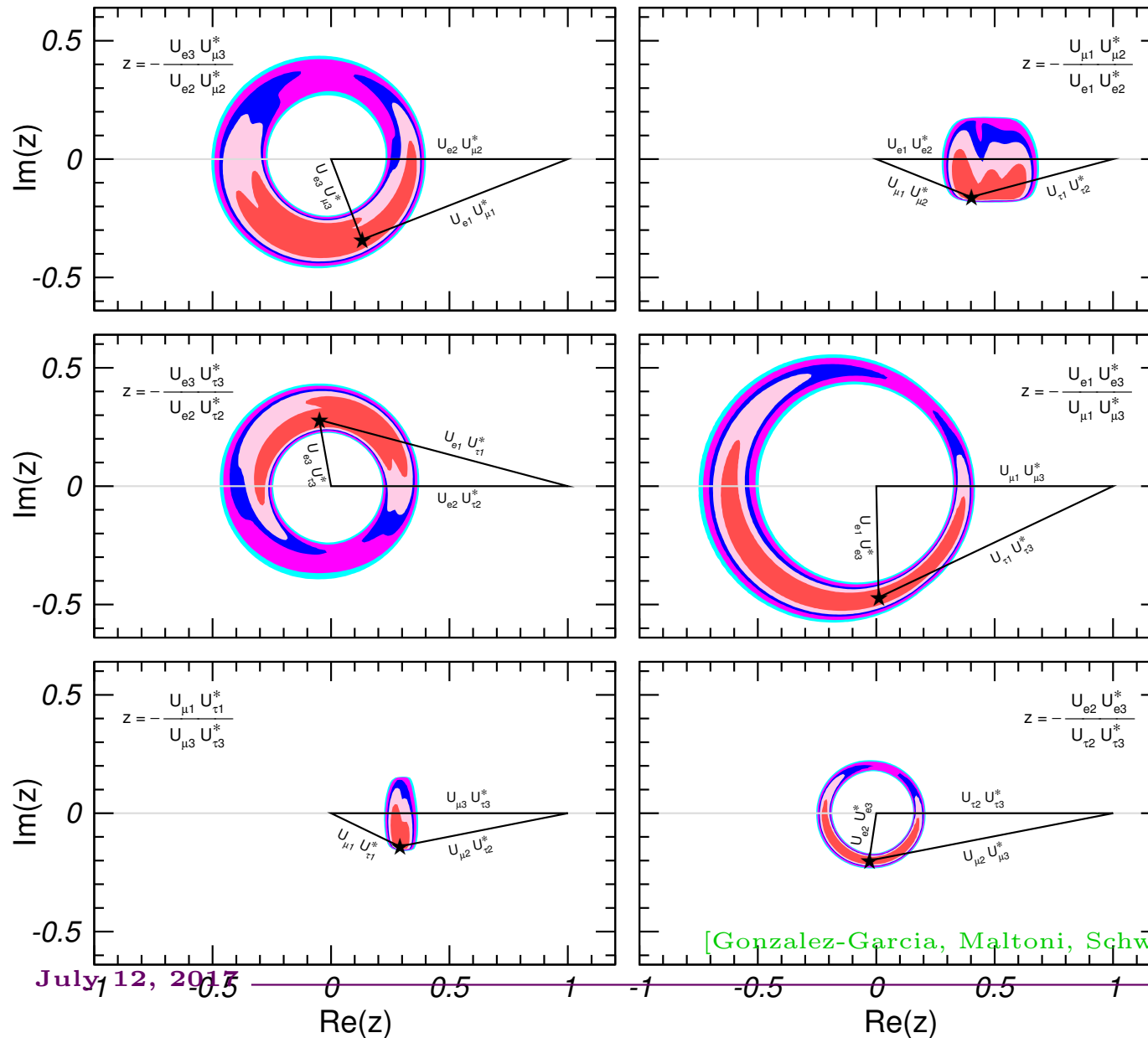


Fig. 28. *Left:* 2D joint posterior distribution between N_{eff} and $\sum m_\nu$ (the summed mass of the three active neutrinos) in models with extra massless neutrino-like species. *Right:* Samples in the $N_{\text{eff}}-m_{\nu, \text{sterile}}^{\text{eff}}$ plane, colour-coded by $\Omega_c h^2$, in models with one massive sterile neutrino family, with effective mass $m_{\nu, \text{sterile}}^{\text{eff}}$, and the three active neutrinos as in the base Λ CDM model. The physical mass of the sterile neutrino in the thermal scenario, $m_{\nu, \text{sterile}}^{\text{thermal}}$, is constant along the grey dashed lines, with the indicated mass in eV. The physical mass in the Dodelson-Widrow scenario, $m_{\nu, \text{sterile}}^{\text{DW}}$, is constant along the dotted lines (with the value indicated on the adjacent dashed lines).

Where We Are (?) [This is Not a Proper Comparison Yet!]

NuFIT 2.0 (2014)



But it is a start...

 [Gonzalez-Garcia, Maltoni, Schwetz, 1409.5439, <http://www.nu-fit.org>]

Solar Neutrinos

We are not done yet!

- see “vacuum-matter” transition

- probe for new physics: NSI, pseudo-Dirac, ...

- probe of the solar interior! “solar abundance problem” (see e.g. 1104.1639)

‘CNO neutrinos may provide information on planet formation!’

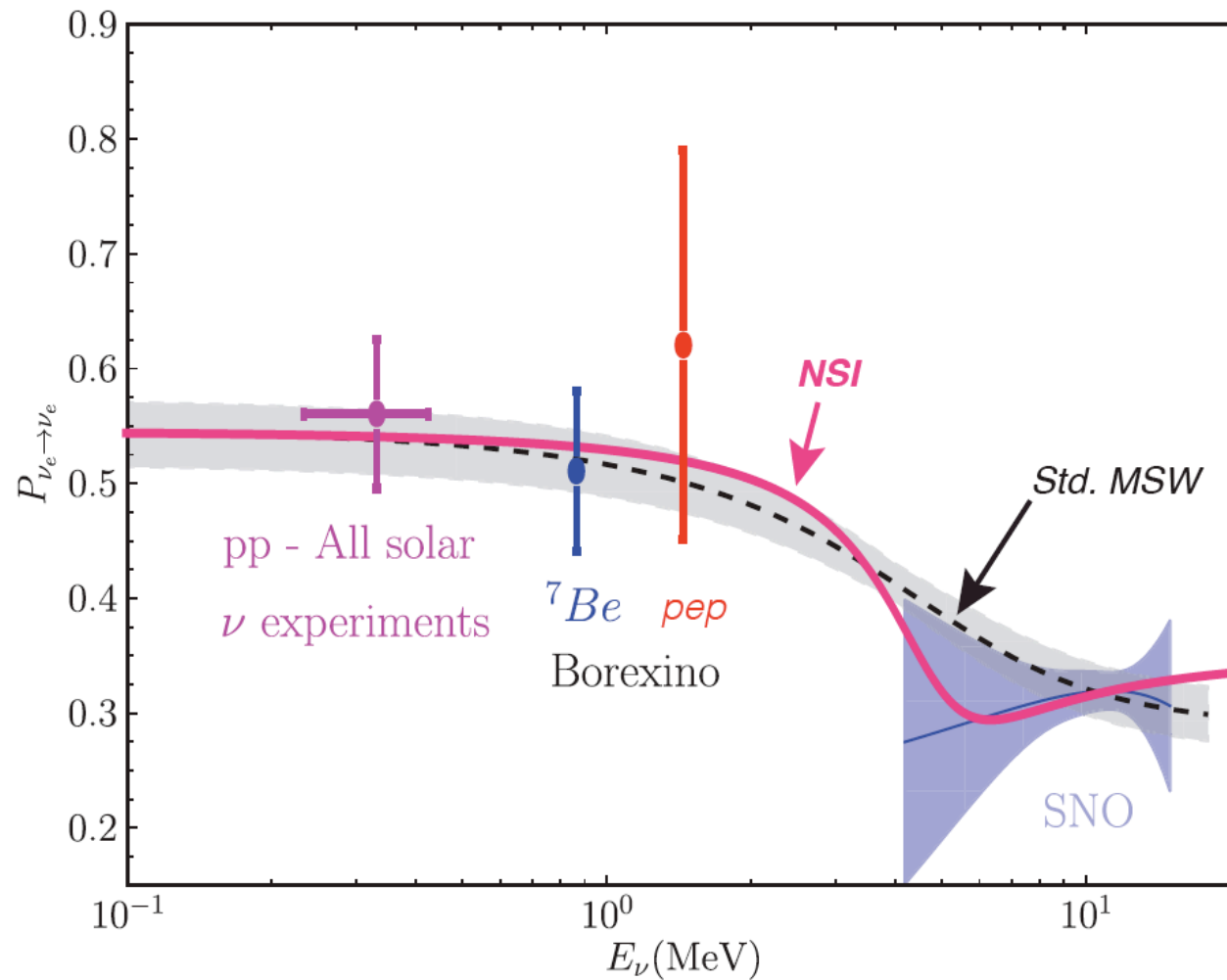


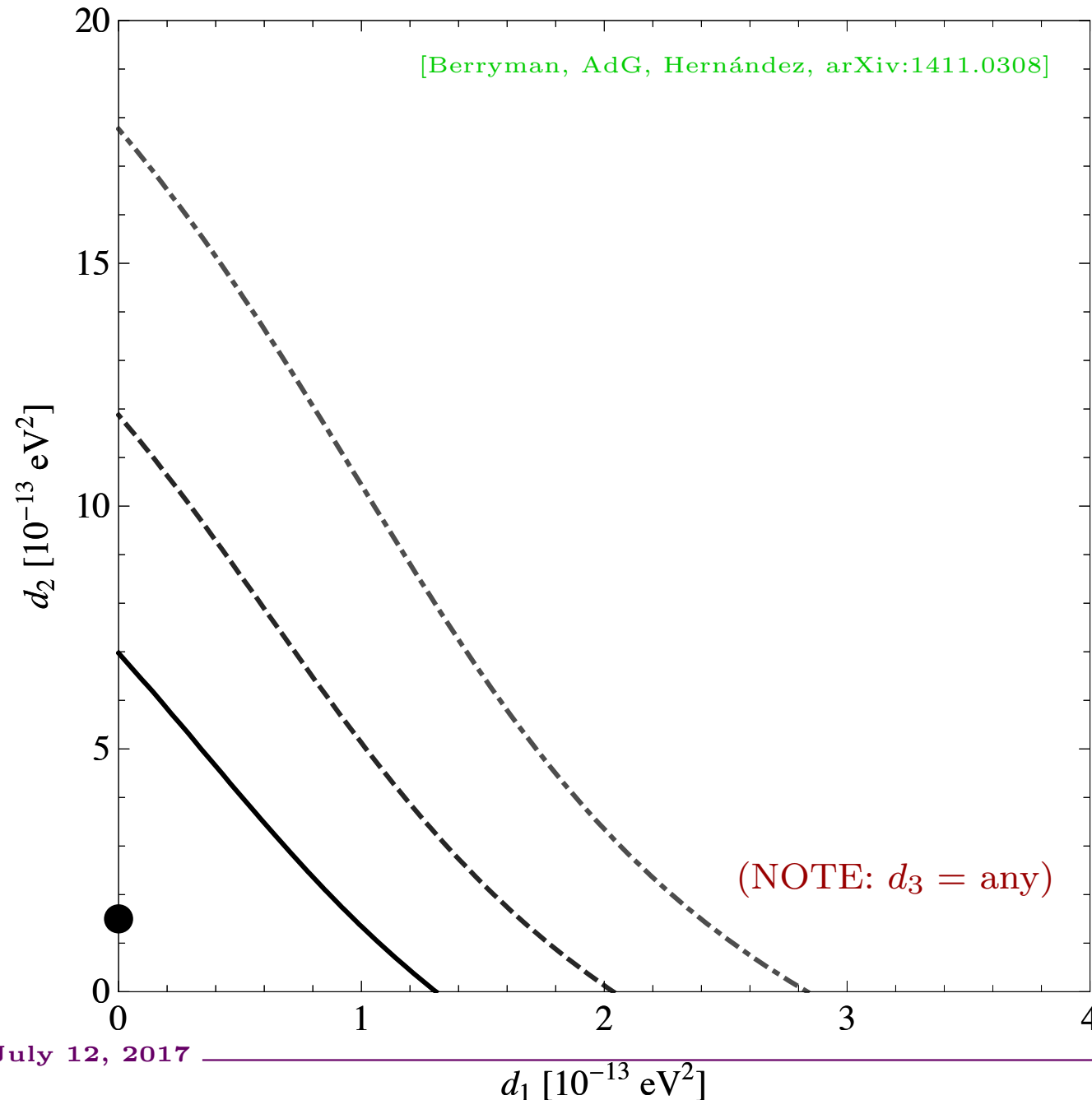
FIG. 1: Recent SNO solar neutrino data [18] on $P(\nu_e \rightarrow \nu_e)$ (blue line with 1σ band). The LMA MSW solution (dashed black curve with gray 1σ band) appears divergent around a few MeV, whereas for NSI with $\epsilon_{e\tau} = 0.4$ (thick magenta), the electron neutrino probability appears to fit the data better. The data points come from the recent Borexino paper [19].

[Friedland, Shoemaker 1207.6642]

July 12, 2017

ν BSM

Constraining the Decay of Neutrinos – Solar Edition



Model-independently,
we know little about
the neutrino lifetime.
 $\nu\text{SM: } \tau > 10^{37} \text{ years.}$

Here, $d_i = m_i / \tau_i$

$$\tau_i = 7 \left(\frac{m_i}{1 \text{ eV}} \frac{10^{-13}}{d_i} \right) \text{ ms}$$

Another Model: Can Neutrino Oscillation Experiments Discover A Fifth Dimension?

André C

western

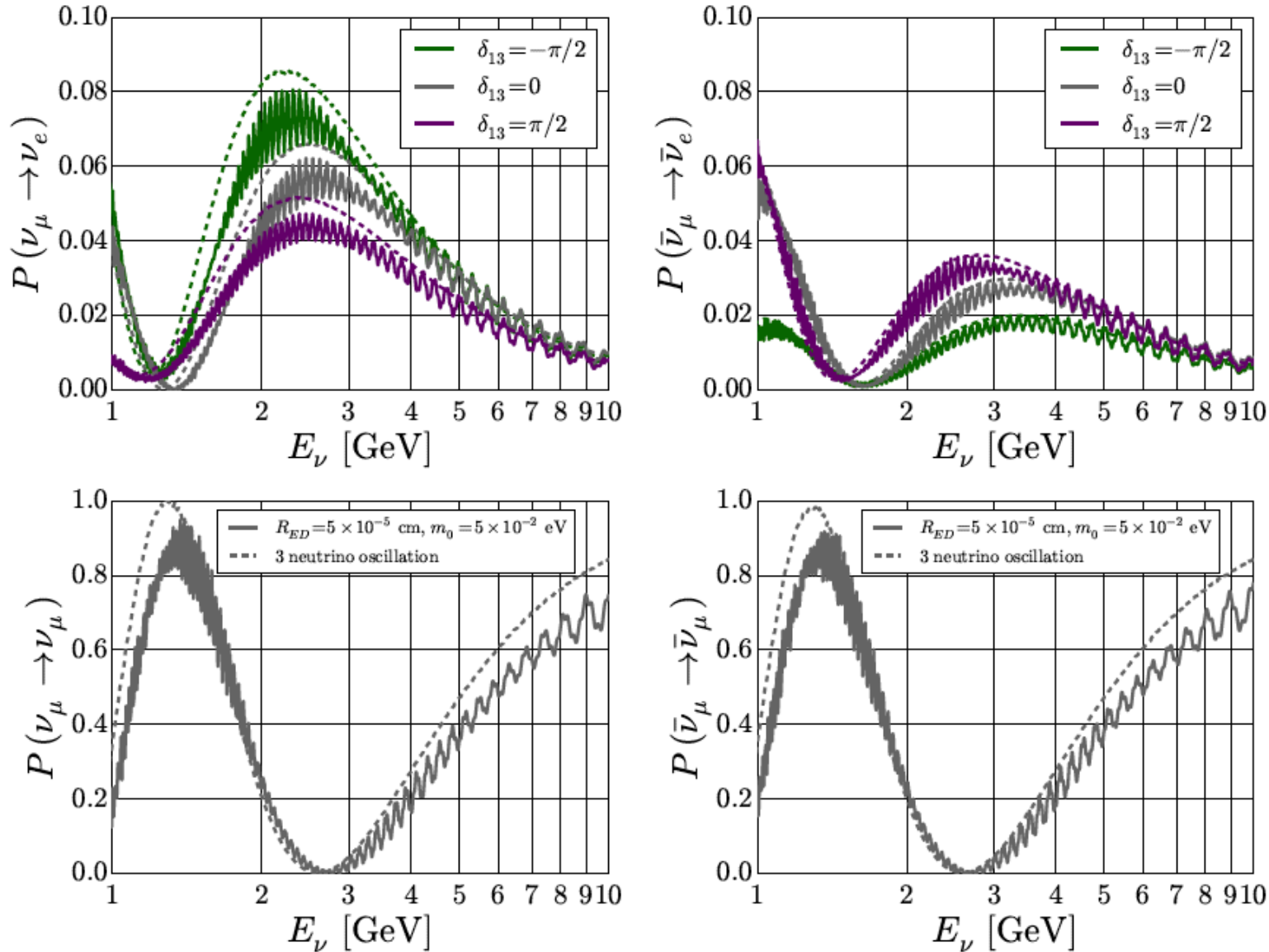


FIG. 1: Oscillation probabilities assuming a three-neutrino framework (dashed) and an LED hypothesis with $m_0 = 5 \times 10^{-2}$ eV and $R_{ED}^{-1} = 0.38$ eV ($R_{ED} = 5 \times 10^{-5}$ cm), for the normal neutrino mass hierarchy, $\Delta m_{13}^2 > 0$. The values of the other oscillation parameters are tabulated in Table I, see text for details. The top row displays appearance probabilities $P(\nu_\mu \rightarrow \nu_e)$ (left) and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ (right), and has curves shown for $\delta_{13} = -\pi/2$ (green), $\delta_{13} = 0$ (gray), and $\delta_{13} = \pi/2$ (purple). The bottom row displays disappearance probabilities $P(\nu_\mu \rightarrow \nu_\mu)$ (left) and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$ (right). [Berryman et al., arXiv:1603.00018]

July 12, 2017

ν BSM

Another Model: Can Neutrino Oscillation Experiments Discover A Fifth Dimension?

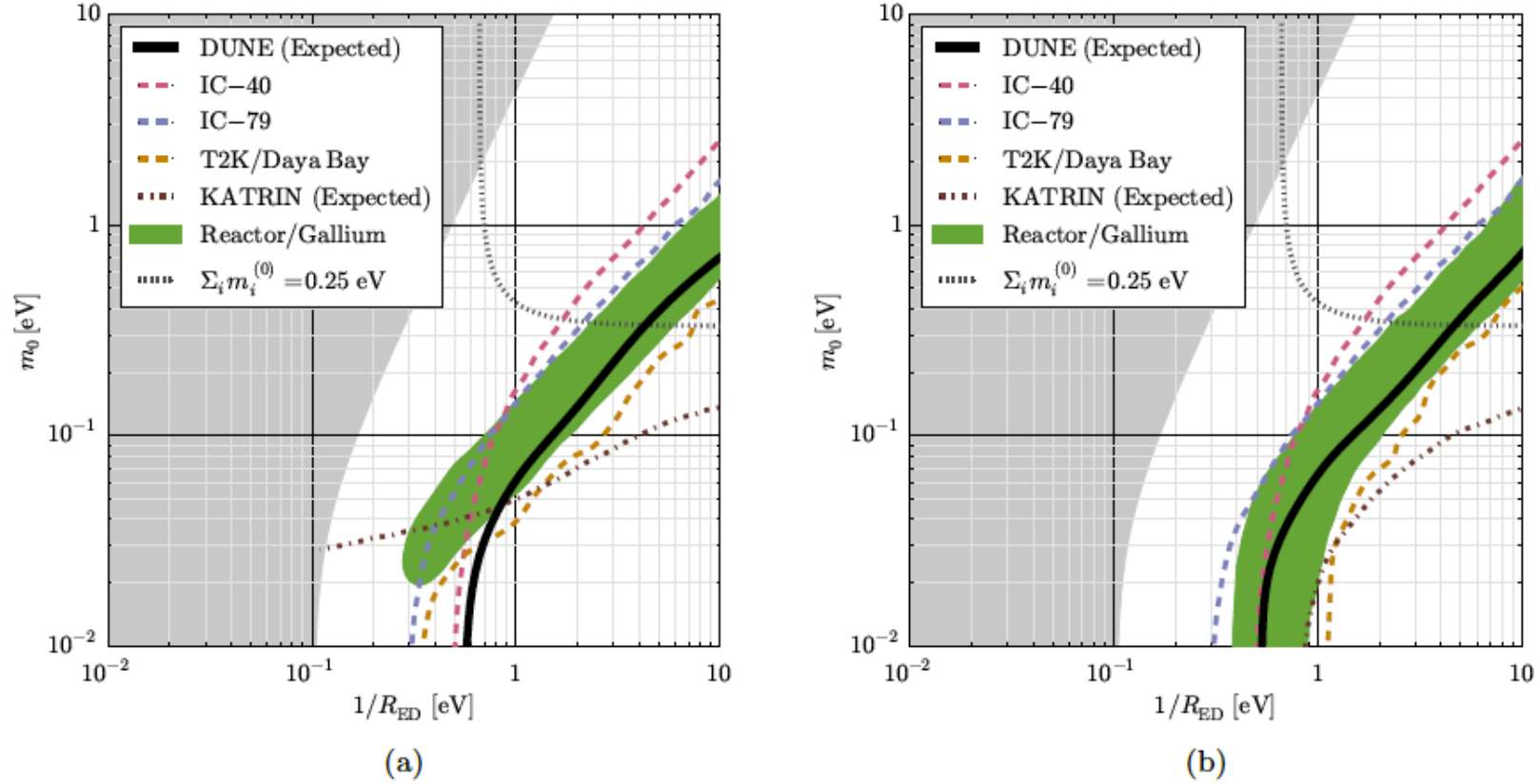


FIG. 3: Exclusion limits in the $R_{\text{ED}}^{-1}-m_0$ plane, assuming either (a) a normal hierarchy or (b) an inverted hierarchy of neutrino masses. The exclusion regions are to the top-left of the relevant curves. Shown are the 95% CL lines from DUNE (black), IceCube-40 (mauve) and Ice-Cube79 (blue) [20], and a combined analysis of T2K and Daya Bay (gold) [18]. We also include the 90% CL line from sensitivity analysis of KATRIN (burgundy) [16]. The shaded green regions are preferred at 95% CL by the reactor anomaly seen in reactor and Gallium experiments [19]. The gray shaded regions are excluded by the measurements of Δm_{21}^2 , as explained in the text. The dotted gray lines are curves along which $\sum_i m_i^{(0)} = 0.25$ eV. Higher values of $\sum_i m_i^{(0)}$ correspond to the regions above and to the right of the dotted gray lines.

[Berryman et al, arXiv:1603.00018]

Another Model: Can Neutrino Oscillation Experiments Discover A Fifth Dimension?

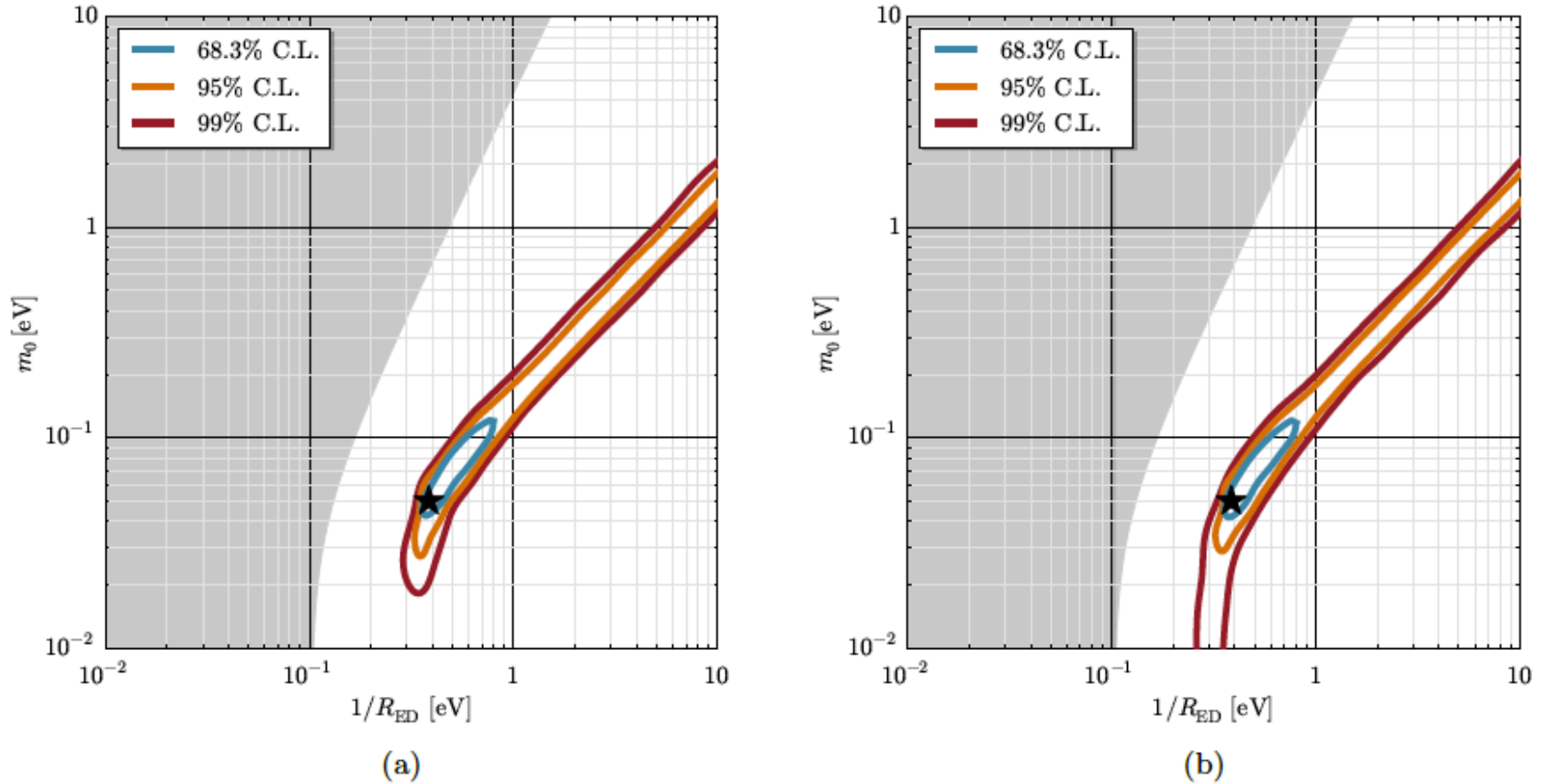


FIG. 4: Expected sensitivity to a non-zero set of LED parameters as measured by DUNE, assuming three years each of neutrino and antineutrino data collection. Fig. 4(a) assumes the normal mass hierarchy (NH) and Fig. 4(b) assumes the inverted mass hierarchy (IH). The LED parameters assumed here are $m_0 = 5 \times 10^{-2}$ eV and $R_{\text{ED}}^{-1} = 0.38$ eV, while $\delta_{13} = \pi/3$. The input values of Δm_{i1}^2 , $i = 1, 2$ are in Table I. The input values for the mixing angles are, for the NH, $\sin^2 \theta_{12} = 0.322$, $\sin^2 \theta_{13} = 0.0247$, $\sin^2 \theta_{23} = 0.581$, and, for the IH, $\sin^2 \theta_{12} = 0.343$, $\sin^2 \theta_{13} = 0.0231$, $\sin^2 \theta_{23} = 0.541$.

[Berryman et al, arXiv:1603.00018]